

# SELF-SUSTAINED ASYMMETRY OF LEPTON-NUMBER EMISSION: A NEW PHENOMENON DURING THE SUPERNOVA SHOCK-ACCRETION PHASE IN THREE DIMENSIONS

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## ABSTRACT

During the stalled-shock phase of our three-dimensional, hydrodynamical core-collapse simulations with energy-dependent, three-flavor neutrino transport, the lepton-number flux ( $\nu_e$  minus  $\bar{\nu}_e$ ) emerges predominantly in one hemisphere. This novel, spherical-symmetry breaking neutrino-hydrodynamical instability is termed LESA for “Lepton-number Emission Self-sustained Asymmetry.” While the individual  $\nu_e$  and  $\bar{\nu}_e$  fluxes show a pronounced dipole pattern, the heavy-flavor neutrino fluxes and the overall luminosity are almost spherically symmetric. LESA seems to develop stochastically from convective fluctuations, it exists for hundreds of milliseconds or more, and it persists during violent shock sloshing associated with the standing accretion shock instability. The  $\nu_e$  minus  $\bar{\nu}_e$  flux asymmetry originates predominantly below the neutrinosphere in a region of pronounced proto-neutron star (PNS) convection, which is stronger in the hemisphere of enhanced lepton-number flux. On this side of the PNS, the mass-accretion rate of lepton-rich matter is larger, amplifying the lepton-emission asymmetry, because the spherical stellar infall deflects on a dipolar deformation of the stalled shock. This deformation persists despite extremely nonstationary convective overturn behind the shock. The increased shock radius in the hemisphere of less mass accretion and minimal lepton-number flux ( $\bar{\nu}_e$  flux maximum) is sustained by stronger convection on this side, which is boosted by stronger neutrino heating due to  $\langle \epsilon_{\bar{\nu}_e} \rangle > \langle \epsilon_{\nu_e} \rangle$ . While these different elements of the LESA phenomenon form a consistent picture, a full understanding remains elusive at present. There may be important implications for neutrino-flavor oscillations, the neutron-to-proton ratio in the neutrino-heated supernova ejecta, and neutron-star kicks, which remain to be explored.

*Subject headings:* supernovae: general — hydrodynamics — instabilities — neutrinos

## 1. INTRODUCTION

Nonradial hydrodynamic instabilities play an important role in the postbounce dynamics of collapsing stellar cores on their way to the onset of supernova (SN) explosions. They also accompany the formation and cooling of the proto-neutron star (PNS). These phenomena include convection in the PNS, large-scale convective overturn below the stalled shock wave during the accretion-shock phase, and the standing accretion shock instability (SASI). We presently add a new phenomenon to this list which we call LESA for “Lepton-number Emission Self-sustained Asymmetry.” Its most conspicuous manifestation is lepton-number flux ( $\nu_e$  minus  $\bar{\nu}_e$ ) emission primarily in one hemisphere, but it also involves a dipole deformation of the strength of PNS convection and of the large-scale convective overturn below the stalled shock.

We first recall these traditional spherical-symmetry breaking instabilities and begin with convection. Prompt post-shock convection leads to the decay of the negative entropy and electron-number gradients left behind by the weakening bounce shock and the shock-breakout burst of electron neutrinos, respectively (Burrows & Fryxell 1992; Janka & Müller 1993; Müller & Janka 1994). It fosters shock expansion and acts as a source of gravitational-wave emission for a period of some ten milliseconds after core bounce (Müller & Janka

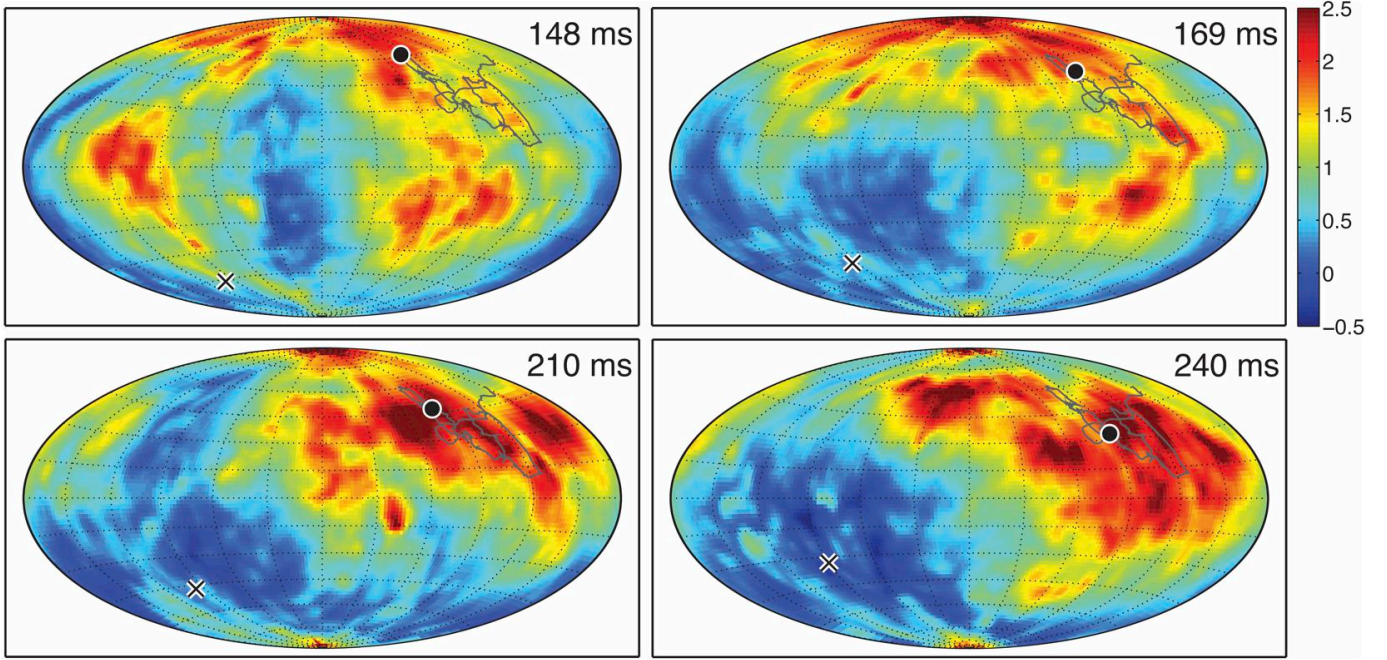
1997; Müller, Janka, & Marek 2013). Inside the nascent neutron star (NS), i.e. below (and possibly also around) the neutrinosphere, Ledoux convection was expected to occur because of the negative lepton number gradient produced by the inward progression of the deleptonization wave associated with neutrino losses (Epstein 1979; Burrows & Lattimer 1988). In two-dimensional (2D) simulations (axial symmetry), PNS convection was first studied by Keil, Janka, & Müller (1996) and later again by Buras et al. (2006a) and Dessart et al. (2006).

Large-scale convective overturn below the stalled shock was predicted by Bethe (1990) and confirmed by the first 2D hydrodynamical simulations (Herant, Benz, & Colgate 1992; Herant et al. 1994; Burrows, Hayes, & Fryxell 1995; Miller, Wilson, & Mayle 1993; Janka & Müller 1995, 1996; Mezzacappa et al. 1998) as well as in 3D (Fryer & Warren 2002, 2004). The driving force is a negative entropy gradient that develops a few tens of milliseconds after core bounce in the neutrino-heating region between the gain radius (where neutrino heating begins to exceed neutrino cooling) and the stalled shock. Convective flows stretch the dwelling time of matter in the gain layer and thus increase the energy deposition by neutrinos. This effect can provide crucial support to the delayed neutrino-heating mechanism: multi-D simulations can yield explosions even when spherically symmetric models fail (e.g., Janka & Müller 1996; Murphy & Burrows 2008; Nordhaus et al. 2010a; Hanke et al. 2012; Dolence et al. 2013; Couch 2013; Couch & O’Connor 2013).

The delayed-explosion mechanism is also aided by SASI which leads to violent shock sloshing motions. This effect

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**Figure 1.** Lepton-number flux ( $\nu_e$  minus  $\bar{\nu}_e$ ) for our  $11.2 M_\odot$  model as a function of direction for the indicated times post bounce. The latitudes and longitudes, indicated by dotted lines, correspond to the angular coordinates of the polar grid of the numerical simulation. The flux in each panel is normalized to its average, i.e., the quantity  $(F_{\nu_e} - F_{\bar{\nu}_e}) / \langle F_{\nu_e} - F_{\bar{\nu}_e} \rangle$  is color coded. The lepton-number emission asymmetry is a large-scale feature which at later times has clear dipole character. The black dots indicate the positive dipole direction of the flux distribution, the black crosses mark the negative dipole direction. The dipole track between 70 and 340 ms is shown as a dark-gray line. Once the dipole is strongly developed, its direction remains essentially stable and shows no correlation with the  $x$ -,  $y$ -, and  $z$ -axes of the numerical grid. The dipole direction is also independent of polar hot spots, which are persistent, local features of moderate amplitude and an artifact connected with numerical peculiarities near the  $z$ -axis as coordinate singularity of the polar grid.

expands the shock, increases the gain layer and, again, can enhance the efficiency of neutrino-energy deposition (Marek & Janka 2009) even when convection is weak or its growth is suppressed because of a small shock-stagnation radius and correspondingly fast infall velocities in the gain layer (Foglizzo, Scheck, & Janka 2006; Scheck et al. 2008). This nonradial instability was first observed in 2D simulations with a full  $180^\circ$  grid (Janka & Müller 1996; Mezzacappa et al. 1998; Janka et al. 2003, 2004), but not immediately recognized as a new effect beyond large-scale convection. It was unambiguously identified in 2D hydrodynamical simulations of idealized, adiabatic (and thus non-convective) post-shock accretion flows (Blondin, Mezzacappa, & DeMarino 2003). SASI was found to possess the highest growth rates for the lowest-order (dipole and quadrupole) spherical harmonics (Blondin & Mezzacappa 2006; Foglizzo et al. 2007; Iwakami et al. 2008) and to give rise to spiral-mode mass motions in 3D simulations (Blondin & Mezzacappa 2007; Iwakami et al. 2009; Fernández 2010; Hanke et al. 2013) or in 2D setups without the constraint of axisymmetry (Blondin & Mezzacappa 2007; Yamasaki & Foglizzo 2008; Foglizzo et al. 2012). The instability can be explained by an advective-acoustic cycle of amplifying entropy and vorticity perturbations in the cavity between accretion shock and PNS surface (Foglizzo 2002; Foglizzo et al. 2007; Scheck et al. 2008; Guilet & Foglizzo 2012) and has important consequences for NS kicks (Scheck et al. 2004, 2006; Nordhaus et al. 2010b, 2012; Wongwathanarat, Janka, & Müller 2010, 2013) and spins (Blondin & Mezzacappa 2007; Rantsiou et al. 2011; Guilet & Fernández 2013), quasi-periodic neutrino emission modulations (Marek, Janka, & Müller 2009; Lund et al. 2010; Tamborra et al. 2013), and SN gravitational-wave sig-

nals (Marek, Janka, & Müller 2009; Murphy, Ott, & Burrows 2009; Müller, Janka, & Marek 2013).

We here report the discovery of a new type of low-mode nonradial instability, LESA, which we have observed in 3D hydrodynamical simulations with detailed, energy-dependent, three-flavor neutrino transport using the PROMETHEUS-VERTEX code. Our current portfolio of simulated 3D models includes an  $11.2 M_\odot$  model that shows violent large-scale convection but no obvious signs of SASI activity during the simulated period of postbounce evolution, a  $20 M_\odot$  model with a long SASI phase, and a  $27 M_\odot$  model in which episodes of SASI alternate with phases of dominant large-scale convection (Hanke et al. 2013; Tamborra et al. 2013). While all models exhibit LESA, with different orientations of the emission dipole, the clearest case is the  $11.2 M_\odot$  model, because the new effect is not overlaid with SASI activity.

To provide a first impression of our new and intriguing phenomenon we show in Fig. 1 the distribution of lepton-number emission ( $\nu_e$  minus  $\bar{\nu}_e$ ) for the  $11.2 M_\odot$  model over the stellar surface at postbounce (p.b.) times of 148, 169, 210, and 240 ms. In each panel, the lepton-number flux is normalized to the instantaneous average and the color scale covers the range from  $-0.5$  to  $2.5$  of this relative measure. We indicate the positive dipole direction with a black dot, the negative direction with a cross. We also show the track of the positive dipole direction as a dark-gray line, ranging from 70 ms p.b., where the dipole begins forming, to the end of the simulation at 340 ms. While at 148 ms the dipole pattern is not yet strong—a quadrupole component is clearly visible and the dipole is still building up as we will see later—the subsequent snapshots reveal a strong dipole pattern with large amplitude: In the negative-dipole direction, the lepton-number

flux is around zero, and even negative in some small regions, whereas in the positive direction it is roughly twice the average and even larger in some small regions.

LESA is a large and conspicuous effect concerning the deleptonization flux. At the same time, it is associated with more subtle dipole deformations of other quantities. In particular, the dipolar lepton-number emission is linked to anisotropic PNS convection, which leads to an aspherical electron distribution in the PNS mantle layer. The emission dipole is additionally fed by a hemispheric mass-accretion asymmetry, which might cause the one-sided enhancement of PNS convection. This accretion asymmetry in turn is a consequence of a dipolar shock deformation that deflects the accretion flow preferentially to one hemisphere. Despite vigorous and highly time-variable, nonstationary convective overturn stirring the postshock region, the shock deformation and mass-accretion asymmetry are maintained for hundreds of milliseconds by a neutrino-heating asymmetry that is tightly linked to the neutrino-emission anisotropy: Because  $\bar{\nu}_e$  have somewhat harder spectra than  $\nu_e$ , neutrino heating on the side of a relatively higher  $\bar{\nu}_e$  flux (the side with lowest lepton-number flux and lowest mass accretion rate) is stronger and sustains the dipolar shock deformation that produces the hemispheric asymmetry of the postshock accretion flow.

This preliminary interpretation suggests that LESAs are not a purely hydrodynamical phenomenon, in contrast to the traditional instabilities, but depends on a complex interaction of hydrodynamic mass flow and neutrino emission and heating.

Our new effect is predominantly a hemispheric asymmetry in these quantities and as such is not a generic 3D effect, but it has not been previously reported in the context of 2D simulations. Actually, indications of LESAs may be present in the O-Ne-Mg core explosions of Wanajo, Janka, & Müller (2011) and in a  $15 M_\odot$  explosion model of Müller et al. (2012b), but it would be difficult to make a strong case. A dipole asymmetry in 2D simulations is restricted to the polar axis of the grid. This symmetry axis, where reflecting boundary conditions are imposed, defines a preferred direction and has various problematic consequences. On the one hand it tends to artificially create hemispheric differences by deflecting the converging flows either inward or outward. On the other hand, the grid axis also directs shock-sloshing motions. The strong presence of the latter in most 2D simulations, where mass flows alternate violently between the poles, may mask or inhibit the lepton-emission asymmetry associated with LESAs.

In the following, we first describe briefly, in Sect. 2, the numerical setup of our 3D simulations and the overall properties of our three progenitor models. In Sect. 3 we study various manifestations of our new phenomenon, ranging from dipole deformations of neutrino-emission properties to asymmetric PNS convection. Next we turn in Sect. 4 to more subtle manifestations in the form of asymmetric accretion and neutrino heating, which however form a feedback loop and as such are the driving engine of the overall effect. In Sect. 5 we string the different elements together and provide an overall scenario that involves the outer feedback mechanism consisting of asymmetric mass accretion and neutrino heating and the inner mechanism of asymmetric electron-density distribution and PNS convection. We conclude in Sect. 6 with a summary and a discussion of possible implications.

## 2. NUMERICAL 3D MODELS

The calculations of our 3D models were performed with the elaborate neutrino-hydrodynamics code PROMETHEUS-VERTEX.

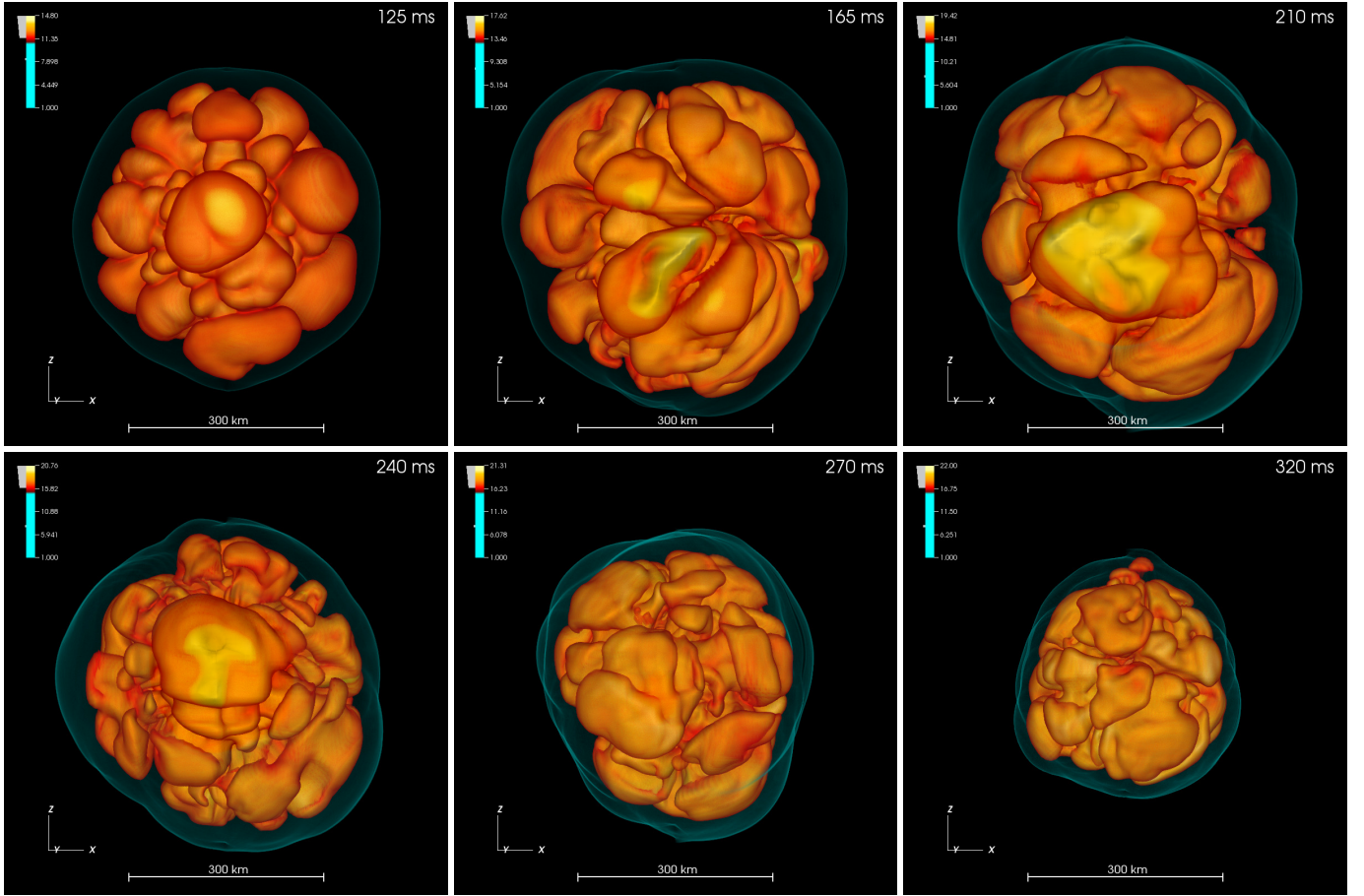
This SN simulation tool combines the hydrodynamics solver PROMETHEUS (Fryxell et al. 1989), which is a dimensionally-split implementation of the piecewise parabolic method (PPM) of Colella & Woodward (1984), with the neutrino transport module VERTEX (Rampp & Janka 2002). VERTEX solves the fully energy-dependent moment equations for the neutrino energy and momentum densities, with  $O(v/c)$  velocity dependence, for spherically symmetric transport problems defined to be associated with every angular bin of the polar grid (“radial rays”) used for the multi-dimensional simulations. The moment equations are closed by a variable Eddington factor relation that is provided by the formal solution of a model Boltzmann equation. An up-to-date set of neutrino interaction rates is applied in VERTEX (see, e.g., Müller et al. 2012b). In the multi-dimensional case, our “ray-by-ray-plus” approach (Buras et al. 2006b) includes non-radial neutrino advection and pressure terms in addition to the radial transport solves. The ray-by-ray approximation implies that we assume the neutrino radiation field to be axially symmetric around the radial direction and thus ignore nonradial components of the neutrino flux. In the simulations presented here, we adopted monopolar gravity but included general relativistic corrections by means of an effective gravitational potential (Marek et al. 2006).

We have performed 3D simulations for the evolution of the  $11.2 M_\odot$  and  $27 M_\odot$  progenitors of Woosley et al. (2002) and the  $20 M_\odot$  model of Woosley & Heger (2007), using the high-density equation of state (EoS) of Lattimer & Swesty (1991) with a nuclear incompressibility of  $K = 220$  MeV. The  $11.2 M_\odot$  and  $27 M_\odot$  stars had been previously investigated in 2D by Buras et al. (2006a), Marek & Janka (2009), Müller et al. (2012b), and Müller et al. (2012a). Our 3D models were computed on a spherical polar grid with an initial resolution of  $n_r \times n_\theta \times n_\phi = 400 \times 88 \times 176$  zones. Later, refinements of the radial grid ensured adequate resolution in the PNS surface region. The innermost 10 km were treated in spherical symmetry to avoid excessive time-step limitations near the polar grid axis. Doing so we took special care to ensure that the convectively unstable layer below the neutrinosphere and the corresponding undershooting region were fully covered by the 3D grid during the entire simulations. Seed perturbations for aspherical instabilities were imposed by hand 10 ms after core bounce by introducing random perturbations of 0.1% in density on the entire computational grid. None of these models led to successful explosions during the simulation period of about 350 ms for the  $11.2$  and  $20 M_\odot$  models and 550 ms for the  $27 M_\odot$  case.

The postbounce hydrodynamics of the  $27 M_\odot$  model, in particular the prominent presence of SASI sloshing and spiral modes, was described in detail in a previous paper (Hanke et al. 2013). Basic properties of the neutrino signal and its detection were subject of a recent paper by Tamborra et al. (2013), highlighting the large-amplitude, quasi-periodic modulations of the radiated luminosities and mean energies associated with the SASI activity. In addition, information about the expected neutrino signal from the  $20 M_\odot$  and  $11.2 M_\odot$  runs was shown. More details of the neutrino emission of all three 3D simulations will be presented in a forthcoming publication (Tamborra et al., in preparation).

The  $27 M_\odot$  and the  $20 M_\odot$  models both show periods of strong SASI activity. In the former case, which was simulated until 550 ms p.b., a second SASI episode occurs after a period of purely convective overturn. On the other hand, the  $11.2 M_\odot$  model does not exhibit any clear evidence of SASI





**Figure 2.** Snapshots of the convective overturn activity during the accretion phase of the  $11.2 M_{\odot}$  model at the indicated p.b. times. Visualized are surfaces of constant entropy: The bluish, semi-transparent envelope is the SN shock, the red-orange-yellow surfaces are entropy structures in the postshock region. Neutrino-heated high-entropy matter expands in typical mushroom-like, buoyant plumes. These features are highly time dependent with bubbles continuously appearing, expanding and rising, and disappearing to give way to a new generation of convective plumes. The direction of strongest lepton-number emission, i.e., the largest excess of the radiation of  $\nu_e$  compared to  $\bar{\nu}_e$  (see text), points towards the observer, above the  $x$ - $y$ -plane at roughly  $45^\circ$  inclination to the  $z$ -axis. A corresponding global, quasi-stationary dipolar deformation of the accretion shock is present but can hardly be recognized without a detailed analysis.

motions but develops the typical signatures of postshock convective overturn in the neutrino-heating layer as evident from our Fig. 2, to be compared with the  $27 M_{\odot}$  case in Fig. 1 of Hanke et al. (2013). In the  $11.2 M_{\odot}$  model, the neutrino-emission variations are distinctly smaller than in the SASI-active models (Tamborra et al. 2013).

In the  $11.2 M_{\odot}$  simulation, first indications of postshock convection become visible at about 80 ms p.b., shortly after a gain region below the stalled shock has developed. Buoyant, mushroom-like plumes appear, which are initially small and then successively replaced by larger ones. At 100 ms p.b., first evidence of shock deformation occurs, and after about 140 ms, convective overturn has attained its full strength with a ratio of maximum to minimum shock radius of up to  $R_{s,\text{max}}/R_{s,\text{min}} \sim 1.35$ . The expansion of the accretion shock continues until about 210 ms p.b., when the average shock radius reaches a maximum of  $\sim 260$  km (see Fig. 11 below). It is followed by a slow but monotonic recession of the average shock radius to only 150 km at the end of the simulation at 350 ms. No explosion has set in until this stage, in contrast to the corresponding 2D calculation with the same microphysics, same numerical grid treatment, and in particular the same radial and angular grid resolution. In the 2D case, the shock continues to expand, supported by large-amplitude shock-sloshing motions along the symmetry axis. More and more favorable

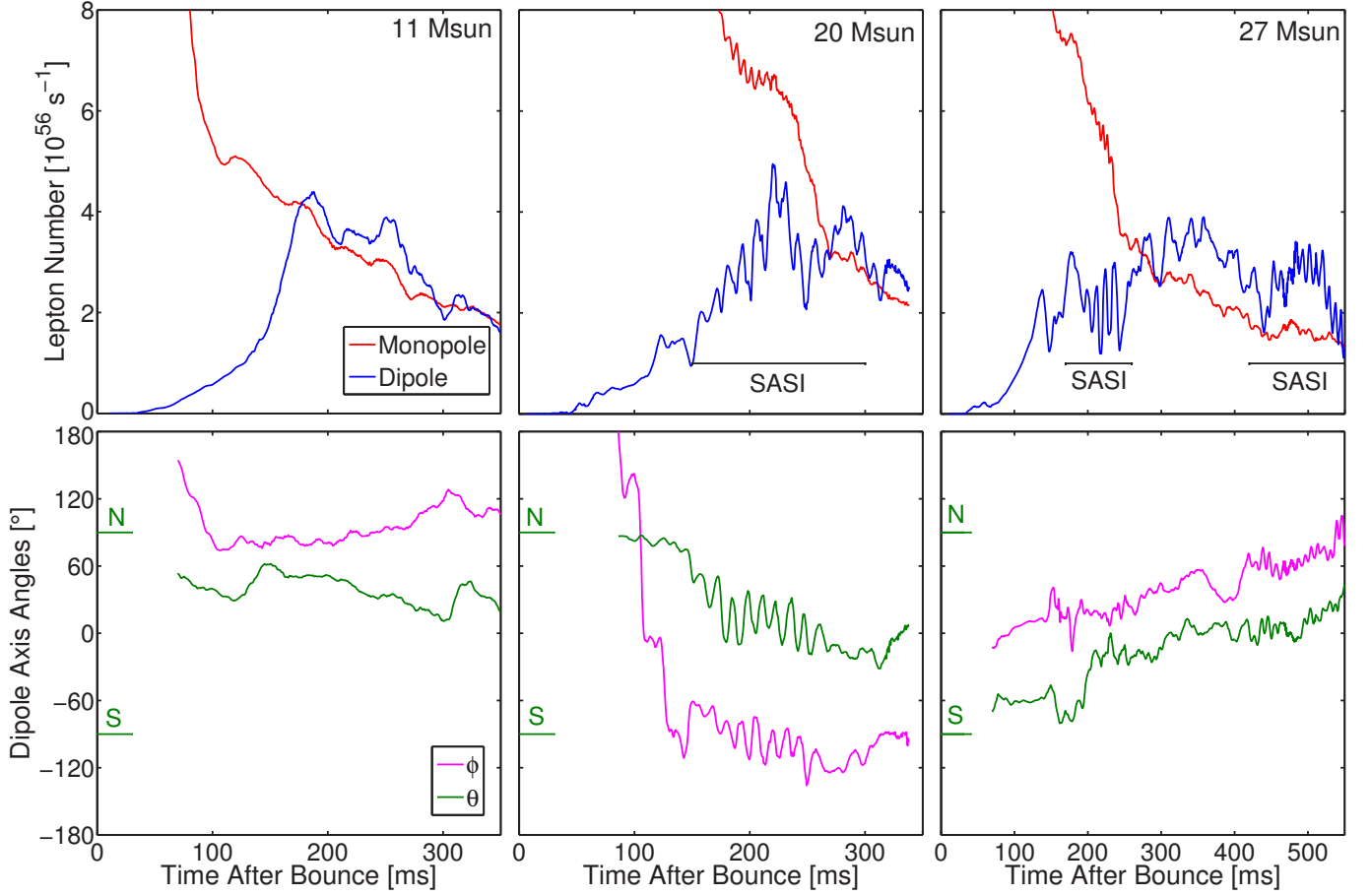
conditions for an explosion develop until finally, at roughly 350 ms p.b., the shock accelerates and triggers an outgoing blast wave, whereas the 3D case at this time shows little promise of an explosion.

Apparently, the 3D setup with the chosen angular resolution (limited by the requirements of computational resources, which are prohibitive for our sophisticated treatment of neutrino transport) is less beneficial for the possibility of a SN explosion by the neutrino-driven mechanism. This finding is in line with recent investigations based on a cruder treatment of neutrino physics, namely a neutrino-light bulb description with simple heating and cooling terms (Hanke et al. 2012; Couch 2013), ray-by-ray neutrino trapping with a parametrized heating strength (Couch 2013), and a ray-by-ray implementation of the isotropic diffusion source approximation (Takiwaki, Kotake, & Suwa 2013). However, the difference between 2D and 3D models is not subject of our present discussion and we next turn to the new phenomenon of asymmetric lepton-number emission.

### 3. STATIONARY DIPOLE ASYMMETRIES OF 3D MODELS

#### 3.1. Evolution of lepton-number emission dipole

We have recently explored the flavor-dependent neutrino emission of our 3D simulations to forecast possible signatures of hydrodynamical instabilities in large-scale neutrino detec-



**Figure 3.** Time evolution of the lepton-number emission ( $\nu_e$  minus  $\bar{\nu}_e$ ) for the 11.2, 20 and 27  $M_{\odot}$  models as labelled. For each model, the upper panels show the overall lepton number flux (monopole of the angular distribution; red curve) and its dipole component (blue curve), and the lower panels display the zenith angle  $\theta$  (green line) and the azimuth angle  $\phi$  (magenta line) of the dipole direction, which describes the track shown for the 11.2  $M_{\odot}$  case in Fig. 1. For the zenith angle we indicate the north- and south-polar grid directions at  $\pm 90^\circ$  on the vertical axis. The monopole evolution depends strongly on the accretion rate and varies between the models, whereas the maximum dipole amplitude is similar in all cases and shows a similar initial growth phase. The dipole persists (and can even grow) during the indicated phases of pronounced SASI activity. The dipole directions are different in all cases, bear no correlation to the numerical grid, and they drift only slowly even during SASI phases.

tors (Tamborra et al. 2013) and as a prerequisite for flavor oscillation studies. A systematic analysis has revealed a long-lasting, nearly stationary dipole asymmetry of the lepton-number ( $\nu_e$  minus  $\bar{\nu}_e$ ) emission from the newly formed NS. In Fig. 1 we have shown typical directional distributions of the lepton-number flux for our 11.2  $M_{\odot}$  model. This pronounced asymmetry builds up in parallel to the development of large-scale convective overturn behind the stalled shock and shows a fairly stable direction, which has no particular correlation with the numerical coordinate grid<sup>3</sup>.

Before attempting a physical interpretation of this puzzling phenomenon, we first collect a number of conspicuous phenomenological manifestations. A natural first question is to see when and how this effect builds up in the course of post-bounce core-collapse evolution and if it is correlated with other symmetry-breaking hydrodynamical instabilities.

To quantify the time evolution of our new effect we consider the lowest-order multipole components of the lepton-number flux as a function of emission direction. To clarify our nor-

malization of the dipole component we note that if the lepton-number flux distribution contains only a monopole and dipole term, then the distribution is  $A_{\text{Monopole}} + A_{\text{Dipole}} \cos \theta$  in coordinates aligned with the dipole direction. When the ratio of these amplitudes is unity, the distribution is proportional to  $1 + \cos \theta$  and the lepton-number flux vanishes in the direction of minimal flux and is twice the average in the direction of maximal flux, corresponding roughly to what we see in Fig. 1.  $A_{\text{Monopole}}$  is nothing but the total rate of lepton number emitted by the evolving PNS, whereas  $A_{\text{Dipole}}$  is 3 times the projection of the total lepton-number flux onto the dipole direction.

Figure 3 shows the evolution of  $A_{\text{Monopole}}$  and  $A_{\text{Dipole}}$  and the dipole direction for our three progenitor models. The total lepton-number emission is at first off-scale, corresponding to the usual prompt  $\nu_e$  burst, and then decreases monotonically with small modulations caused by large-scale convection and concomitant variations of the postshock accretion flow. The overall lepton-number emission is fed by the mass-accretion flow so that it is not surprising that the monopole strength depends considerably on the progenitor model.

In all models, a dipole component becomes first discernible at about 50 ms p.b., grows for 100–150 ms, and later begins to decrease, more or less in parallel with the overall decline of the lepton-number emission. In this later phase, the dipole

<sup>3</sup> The orientation of the coordinate system in our sky-plots of Figs. 1, 6, and 7 is such that the north-south direction corresponds to the z-axis of the numerical grid, the center of the plot is the  $-x$  direction, and the left and right extreme points correspond to the  $+x$  direction. The half-way points on the equator belong to the  $+y$  (left) and  $-y$  directions.

amplitude sometimes exceeds the monopole, meaning that in the negative dipole direction, the lepton-number flux is somewhat negative (excess of  $\bar{\nu}_e$  over  $\nu_e$  emission). The overall dipole strength is similar in all three progenitor models, at the peak reaching a value of  $3\text{--}4 \times 10^{56} \text{ s}^{-1}$ .

The dipole orientation on the computational polar grid is expressed by latitudinal and azimuthal polar angles  $\theta$  and  $\phi$ , respectively. The zenith angle,  $\theta$ , varies from  $\pi/2$  (north pole of numerical grid) to  $-\pi/2$  (south pole), whereas  $-\pi \leq \phi \leq \pi$  is measured relative to the  $x$ -axis of the grid. The dipole direction slowly drifts, but remains fairly stable once the dipole is well developed. This conclusion also follows from the dipole's sky-track shown as a dark-gray line in Fig. 1 for the  $11.2 M_\odot$  case. It is remarkable that this behavior is quite similar in the higher-mass (20 and  $27 M_\odot$ ) progenitors, where phases with dominant large-scale convection alternate with phases of pronounced SASI activity, which are indicated in Fig. 3 by horizontal bars. The SASI action is clearly visible in the form of small periodic modulations of the overall deleptonization flow and much larger modulations of the dipole strength and direction. Yet, even these modulations are only a small variation of the dipole strength and its orientation in space.

These simple observations already suggest that the LESA phenomenon must physically depend on a complicated interplay of different effects. The initial growth over 100–150 ms parallels the growth of large-scale convection in the gain region, suggesting gain-region convection as the primary engine. On the other hand, the persistence throughout SASI episodes and the near-universal dipole strength suggest that LESA must also be anchored to deeper regions. We will see that indeed it originates in the PNS convection region deep below the neutrinospheres.

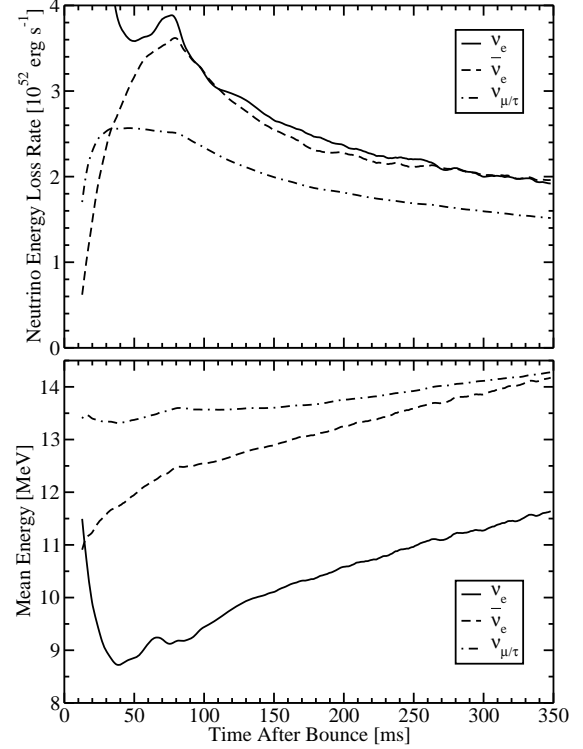
### 3.2. Overall neutrino emission properties

Before turning to physical interpretations, however, we first continue with our description of phenomenological observations in our numerical models. In particular, one may wonder if the overall neutrino emission parameters exhibit any peculiarities, but this is not the case. We specifically show in Fig. 4 the evolution of the overall energy-loss rate for the  $11.2 M_\odot$  model in the three species  $\nu_e$ ,  $\bar{\nu}_e$ , and  $\nu_x$ , i.e., we display the  $4\pi$ -integrated energy fluxes,

$$\dot{E}_\nu(t) \equiv \int_{4\pi} d\Omega R^2 F_e(\mathbf{R}, t), \quad (1)$$

where  $F_e(\mathbf{R}, t)$  is the ray-by-ray computed energy-flux density at a point  $\mathbf{R}$  of a chosen sphere with radius  $R = |\mathbf{R}|$ . The quantity  $\dot{E}_\nu(t)$  is usually called “luminosity” but it is not measurable in the multi-dimensional case by observers at any location. The bottom panel of Fig. 4 shows the corresponding  $4\pi$ -averaged mean energies,  $\langle \epsilon_{\nu_i} \rangle$ , which are defined as the ratios of energy-loss rates to number-loss rates.

This figure reveals the usual behavior during the postbounce accretion phase (compare, e.g., with results by Marek & Janka 2009; Marek, Janka, & Müller 2009; Janka et al. 2012).  $\dot{E}_{\nu_e}$  after the shock-breakout burst is very close to  $\dot{E}_{\bar{\nu}_e}$  or even slightly larger, while  $\langle \epsilon_{\nu_e} \rangle$  exceeds  $\langle \epsilon_{\bar{\nu}_e} \rangle$  by a few MeV. Heavy-lepton neutrinos have significantly lower individual luminosities because their production in the accretion layer of the PNS is less efficient due to the lack of charged-current processes, and  $\langle \epsilon_{\nu_x} \rangle$  is only slightly larger than  $\langle \epsilon_{\bar{\nu}_e} \rangle$  because energy transfers in neutrino-nucleon scatterings reduce the high-energy



**Figure 4.** Time evolution of spherically averaged neutrino emission properties (laboratory frame) for the  $11.2 M_\odot$  model. *Top:* Energy loss rates, integrated over all directions, for  $\nu_e$ ,  $\bar{\nu}_e$ , and (one kind of)  $\nu_x$ . *Bottom:* Mean energies, averaged over all directions. These results do not show any peculiarities and are similar to comparable 1D and 2D simulations.

spectrum of  $\nu_x$  diffusing outward from their deeper production layers (Raffelt 2001; Keil, Raffelt, & Janka 2003).

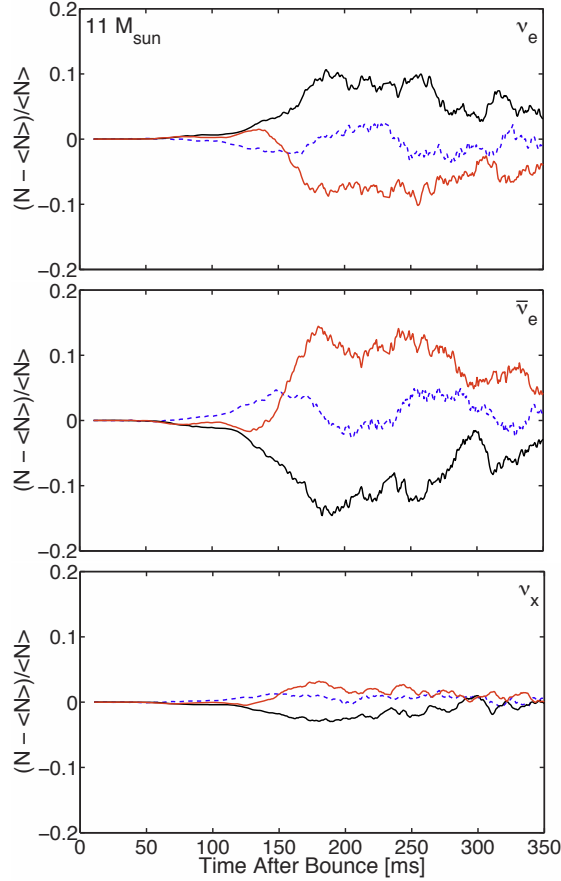
### 3.3. Other flux asymmetries

The LESA phenomenon is a conspicuous order-unity effect of the directional lepton-number flux variation, but also shows up in other quantities, notably in the directional variation of the individual  $\nu_e$  and  $\bar{\nu}_e$  fluxes. To illustrate this point we show in Fig. 5 these number fluxes as they would be seen by a distant observer relative to their directional averages. We use three viewing directions oriented relative to the lepton-number dipole axis, i.e., an observer located in the direction of maximal lepton-number flux (black lines), the opposite direction of minimal lepton-number flux (red lines), and a typical direction transverse to the dipole axis (dashed blue lines).

A distant observer measures the integrated intensity over a hemisphere of the radiating NS surface, projected on the viewing direction. The corresponding “averaging” over the visible hemisphere eliminates small-scale variations. To evaluate the observational quantities we follow the procedure described in Sect. 3.1 of Müller, Janka, & Wongwanarat (2012) and calculate the observable flux, here the number-flux  $N$ , from the ray-by-ray-computed number-flux densities,  $F_n(\mathbf{R})$ , at points  $\mathbf{R}$  on the radiating surface by an integration over the visible hemisphere, cf. Eq. (7) in Müller, Janka, & Wongwanarat (2012):

$$N(t) = 2 \int_{\text{vis.hem.}} dA \cos \vartheta F_n(\mathbf{R}, t) \left( 1 + \frac{3}{2} \cos \vartheta \right). \quad (2)$$

Here  $\vartheta$  is the zenith angle at point  $\mathbf{R}$  on the radiating sphere, i.e., the angle between the normal vector of the surface el-



**Figure 5.** Time evolution of the  $\nu_e$ ,  $\bar{\nu}_e$ , and heavy-lepton neutrino ( $\nu_x$ ) number fluxes (top to bottom) relative to their directional averages for the  $11.2 M_\odot$  model. We show hemispheric averages (accounting for projection effects; see text) as seen by distant observers who are located approximately in the direction of maximal lepton-number emission (black), in the opposite direction (red) and in a representative transverse direction (dashed blue). The  $\nu_e$  and  $\bar{\nu}_e$  fluxes each exhibit a strong dipolar asymmetry, (anti-)aligned with the lepton-number flux dipole, whereas the  $\nu_x$  flux is nearly isotropic except for a small enhancement in the hemisphere of smallest lepton-number flux (red line).

ement  $dA$  and the observer direction. An analogous relation pertains to the energy luminosity,  $L$ , as a function of the energy-flux densities,  $F_e(\mathbf{R})$ ,

$$L(t) = 2 \int_{\text{vis.hem.}} dA \cos \vartheta F_e(\mathbf{R}, t) \left( 1 + \frac{3}{2} \cos \vartheta \right), \quad (3)$$

cf. Eq. (5) in Müller, Janka, & Wongwathanarat (2012). The integrands of Eqs. (2) and (3) account for projection effects of the radiating surface elements and limb darkening. In the free-streaming limit, the flux density  $F(\mathbf{R})$  declines like  $R^{-2}$  with distance  $R = |\mathbf{R}|$  from the source center, while the surface element  $dA = R^2 d\Omega$  ( $d\Omega$  being the solid angle) increases with  $R^2$ . Therefore, the product  $dA F(\mathbf{R})$  becomes constant and the integral value is independent of the chosen surface of integration.

Figure 5 shows that in the early phase of postshock convection the directional emission asymmetry remains small. At about 150 ms, however, a stable dipolar pattern emerges and reaches maximum amplitudes of around 10% for  $\nu_e$  and 15% for  $\bar{\nu}_e$  at roughly 180 ms after bounce. A positive amplitude for  $\nu_e$  is correlated with a negative one for  $\bar{\nu}_e$  and vice versa, and local maxima (minima) of the  $\nu_e$  emission generally coincide in time with minima (maxima) of the  $\bar{\nu}_e$  emission. After

$t \sim 180$  ms a slow, overall trend of decay of the dipolar emission asymmetry begins, in agreement with our earlier finding in the lepton-number flux, although the relative strength of the lepton-number asymmetry remains large. Note also that we show here the evolution as observed from a fixed direction so that overall trends of the fluxes can be partly caused by a drift in the dipole direction.

The dipole asymmetry is large in the  $\nu_e$  and  $\bar{\nu}_e$  fluxes, whereas heavy-lepton neutrinos,  $\nu_x$ , exhibit at most a few-percent effect. The  $\nu_x$  emission is slightly enhanced in the direction of small lepton-number (high  $\bar{\nu}_e$ ) flux.

Figure 6 provides similar information for the  $11.2 M_\odot$  model in the form of sky maps for all viewing directions of a distant observer. The temporal stability of the dipole pattern justifies time averaging instead of individual snapshots. In particular, we average over 150–250 ms p.b., when the dipole effect is particularly strong. The left column provides the luminosity,  $L$ , for  $\nu_e$ ,  $\bar{\nu}_e$ ,  $\nu_x$ , as well as  $\nu_e$  plus  $\bar{\nu}_e$ , and  $\nu_e$  minus  $\bar{\nu}_e$ , all normalized to their directional maxima except for the difference plot, which is normalized to the all-sky average of  $L_{\nu_e} + L_{\bar{\nu}_e}$ . The right column shows analogous information for the corresponding number fluxes,  $N$ .

Both luminosity and number fluxes clearly show the emission dipole (anti-)aligned with the lepton-number dipole axis. While the maximum variation amplitudes of  $\nu_e$  and  $\bar{\nu}_e$  fluxes are approximately  $\pm 10\%$  in the two dipole directions, heavy-lepton neutrinos show just about  $\pm 2\%$  variations. In contrast to the individual luminosities and number fluxes, the sums  $L_{\nu_e} + L_{\bar{\nu}_e}$  and  $N_{\nu_e} + N_{\bar{\nu}_e}$ , vary only on the few-percent level. We also note that the relative variation of the energy-flux difference,  $L_{\nu_e} - L_{\bar{\nu}_e}$ , is a bit smaller than the hemispheric variation of the number-flux difference  $N_{\nu_e} - N_{\bar{\nu}_e}$ . Most importantly, while the former can be positive or negative, the latter is positive in all directions. This shift of the asymmetry variation in the luminosity difference corresponds to considerably larger  $\bar{\nu}_e$  energies relative to  $\nu_e$ .

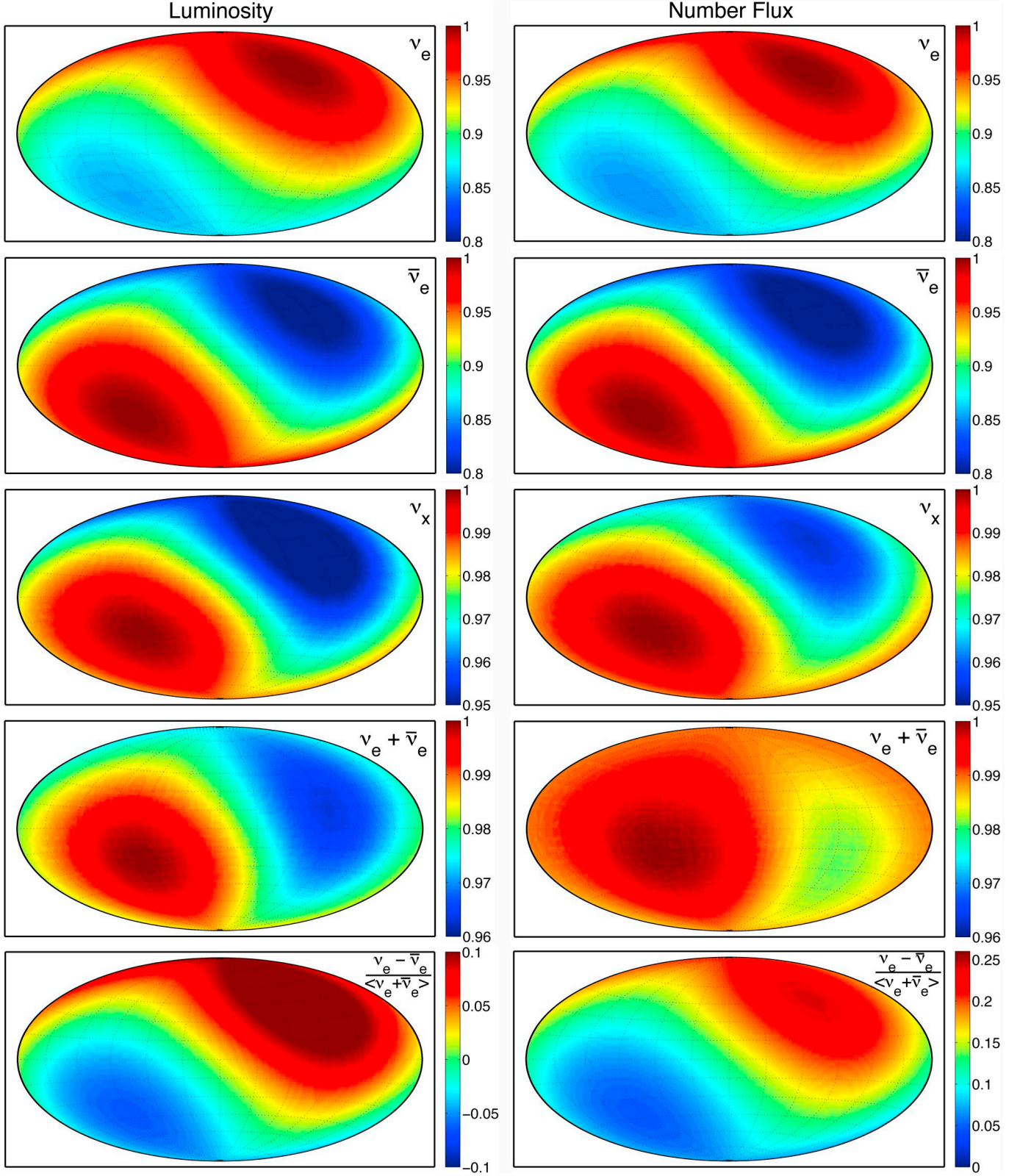
In contrast, the  $27 M_\odot$  run with its episodes of strong SASI shock sloshing and spiralling motions (see Hanke et al. 2013) exhibits large-amplitude, quasiperiodic neutrino emission modulations with dipolar asymmetry in all flavors (Tamborra et al. 2013). In addition, however, the  $27 M_\odot$  model also shows a stationary lepton-number emission dipole, i.e., a nearly stationary and non-oscillating dipole in the lepton-number flux ( $\nu_e$  minus  $\bar{\nu}_e$ ). We present a sky-map of the  $\bar{\nu}_e$  number flux as well as the total  $\nu_e$  plus  $\bar{\nu}_e$  flux in Fig. 7. To avoid any confusion with SASI activity, we show a time-averaged signal here as seen by a distant observer taken between the two episodes of SASI activity, i.e., integrated over the p.b. interval of 260–360 ms. In qualitative agreement with the  $11.2 M_\odot$  case, there is a clear dipole feature in the  $\bar{\nu}_e$  flux, whereas in the sum flux the dipole variation is weak—the individual  $\nu_e$  and  $\bar{\nu}_e$  fluxes are again anti-correlated.

The LESA dipole direction of the  $27 M_\odot$  case is not correlated with the main direction of SASI sloshing that exists during 170–260 ms in this model. It is also uncorrelated with the LESA dipole direction of the  $11.2 M_\odot$  model, and uncorrelated with the numerical grid.

### 3.4. Radial evolution of the emission dipole

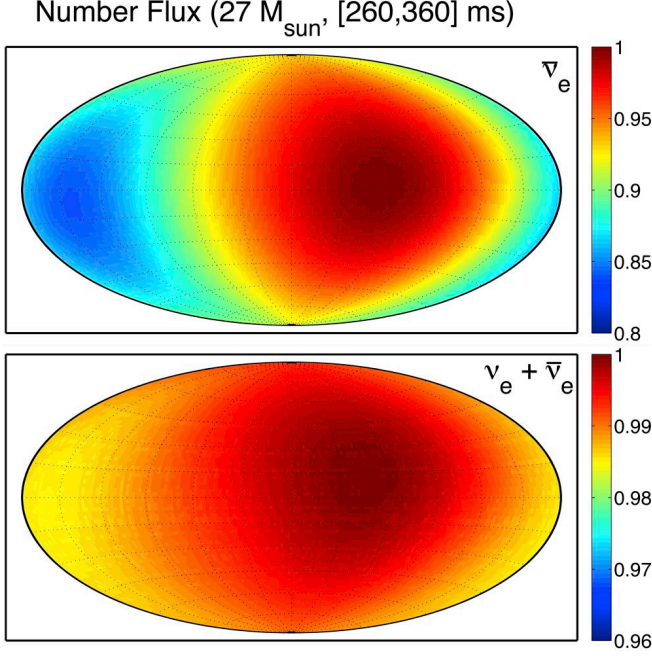
We next investigate the spatial origin of the lepton-number flux asymmetry. To this end we consider the evolutionary stage at 210 ms p.b. of the  $11.2 M_\odot$  model when the lepton-number dipole has reached a large value. Figure 8 shows the radial evolution of the lepton-number ( $\nu_e$  minus  $\bar{\nu}_e$ ) flux for



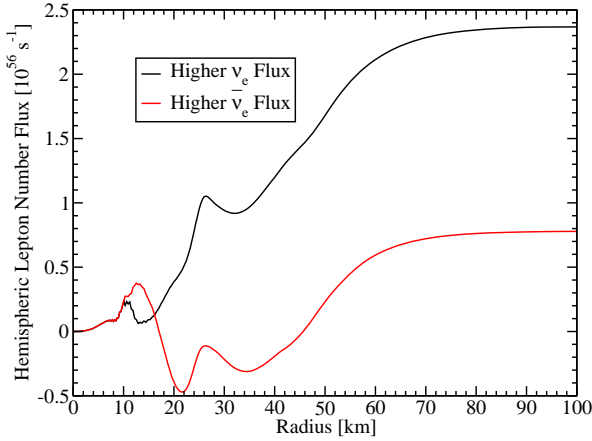


**Figure 6.** Energy luminosity,  $L$  (left), and number flux,  $N$  (right), for the  $11.2 M_{\odot}$  simulation as functions of viewing direction for a distant observer. The latitudes and longitudes indicated by dotted lines follow the angular coordinate directions of the computational grid. The quantities are hemispheric averages (including projection effects as described in the text) and time integrated over 150–250 ms post bounce. The first three rows show the  $\nu_e$ ,  $\bar{\nu}_e$ , and heavy-lepton neutrino ( $\nu_x$ ) fluxes, while the fourth row shows  $L_{\nu_e} + L_{\bar{\nu}_e}$  and  $N_{\nu_e} + N_{\bar{\nu}_e}$ . The plotted quantities are normalized to their maximum. In each row the color scale of both images is the same, but the ranges are different in different rows. The bottom row shows the relative excess of  $\nu_e$  over  $\bar{\nu}_e$  emission, i.e.,  $(L_{\nu_e} - L_{\bar{\nu}_e}) / \langle L_{\nu_e} + L_{\bar{\nu}_e} \rangle$  (left) and  $(N_{\nu_e} - N_{\bar{\nu}_e}) / \langle N_{\nu_e} + N_{\bar{\nu}_e} \rangle$  (right). The denominators are averages over all observer directions. In one hemisphere, the lepton number-emission ( $\nu_e$  minus  $\bar{\nu}_e$ ) is significantly smaller than the average, while in this hemisphere the energy luminosity of  $\bar{\nu}_e$  exceeds that of  $\nu_e$ . In contrast, the number and energy fluxes of  $\nu_e$  plus  $\bar{\nu}_e$  as well as those of  $\nu_x$  deviate from isotropy only on the few-percent level.





**Figure 7.** Sky-maps for the  $27 M_{\odot}$  model analogous to second and fourth panels in the right column of Fig. 6. The time interval of integration, 260–360 ms p.b., is between two episodes of strong SASI activity. The behavior of the heavier-mass models is qualitatively similar to the  $11.2 M_{\odot}$  case but the spatial orientation of the lepton-emission dipole is different in each case.



**Figure 8.** Radial evolution of the lepton-number emission in the hemisphere where the lepton flux is maximal (black) and minimal (red) for the  $11.2 M_{\odot}$  simulation at 210 ms p.b. The fluxes are integrated over the hemispheres without projection effects so that their sum is the total lepton-number flux traversing a spherical surface of given radius. The lepton-number flux asymmetry originates mostly from deep inside the PNS, i.e., from the hot PNS mantle below the neutrinosphere that is located at approximately 35 km, whereas a more spherically symmetric component of the lepton-number flux develops in the surrounding, semi-transparent cooling layer and is fed by the accretion of lepton-rich material.

the two hemispheres where it is maximal and minimal, respectively. The integration avoids any projection or observer effects—the sum of the two hemispheric values yields the total lepton-number flux traversing a spherical shell of given radius. It is intriguing that most of the hemispheric difference builds up in the PNS mantle layer *below* the (average) neutrinospheres, which are located here at around 35 km. At this radius, the lepton-flux difference has nearly reached its asymp-

totic value, whereas only about 20–25% (or  $3\text{--}4 \times 10^{55} \text{ s}^{-1}$ ) arise at larger radii and are therefore more directly associated with the hemispheric asymmetry of the accretion flow.

A different way of visualizing the radial evolution of the lepton-number flux is to study it along individual radial “rays” of our transport scheme. To this end we have performed a cut of our  $11.2 M_{\odot}$  model in a plane containing the dipole direction at 210 ms p.b. Figure 9 shows the result with a color coding corresponding to the radial lepton-number flux as a function of location in this cut plane. The downward direction in the plots is the direction of maximum lepton-number flux. It is apparent that this hemisphere shows stronger convection inside the PNS than the other hemisphere. The flux asymmetry arises far below the average neutrinosphere, here indicated by a white circle.

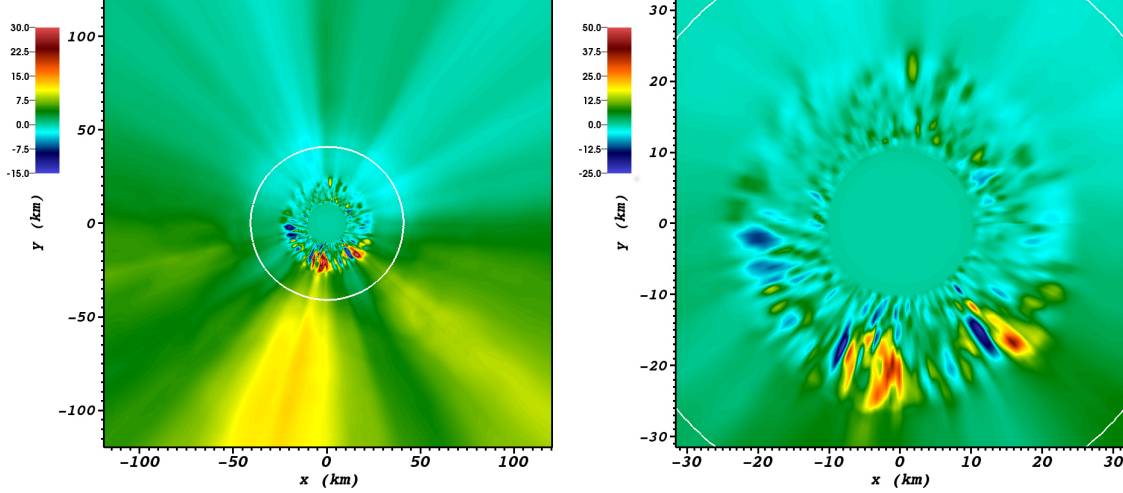
Most of the overall lepton-number emission (the monopole of the emission distribution) builds up in the envelope (i.e., the neutrino-cooling) region above the NS and is fed by the accretion downflows of lepton-rich material, whereas most of the dipole builds up around the PNS convection zone deep inside the NS and below the neutrinosphere. While the accretion flow also shows a dipole asymmetry as we will see, it is not responsible for the main effect of the asymmetry of the lepton-number emission.

### 3.5. Asymmetry of electron density distribution

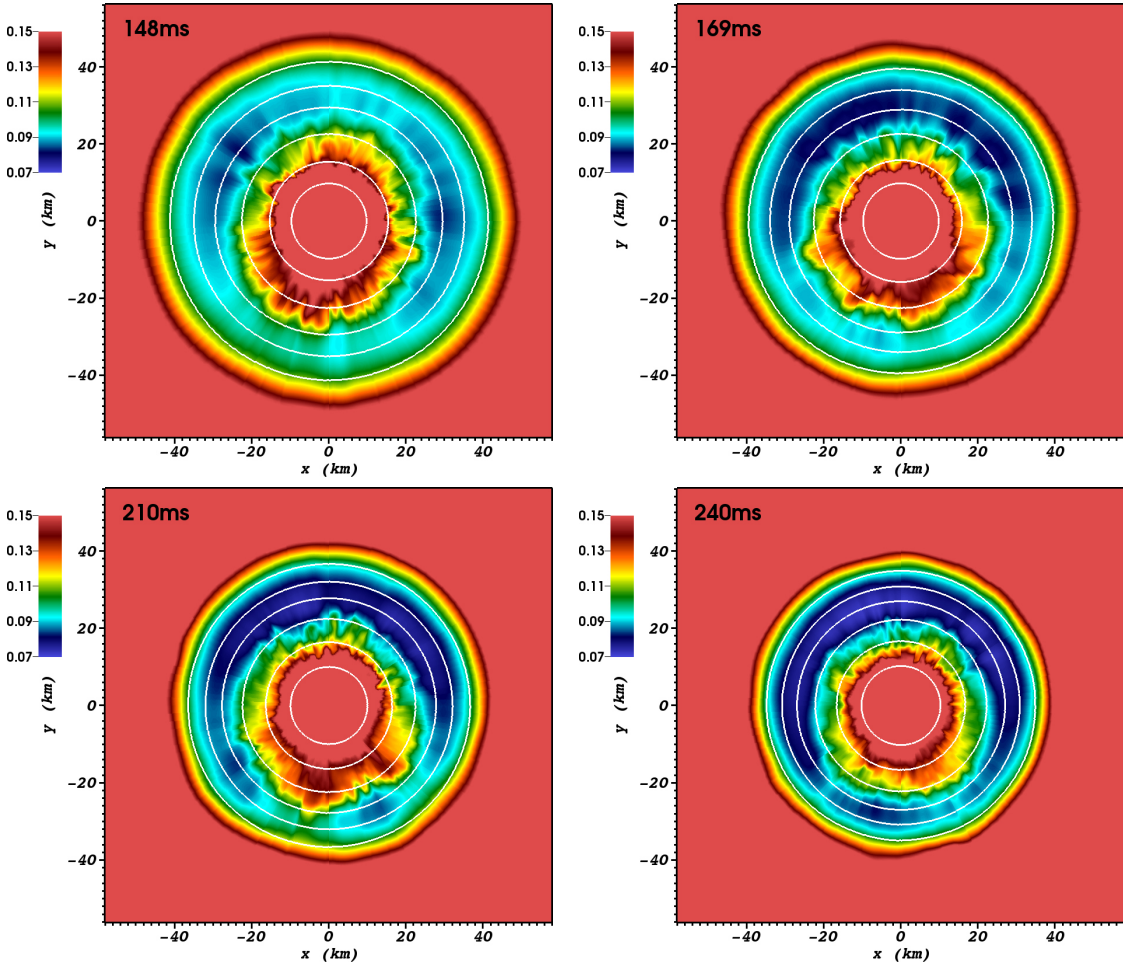
Most of the lepton number stored in the PNS and its accretion layer is in the form of electrons, whereas it is emitted in the form of a  $\nu_e\text{--}\bar{\nu}_e$  number-flux difference. Therefore, it is instructive to inspect the electron density distribution in those regions of the PNS where the lepton-flux dipolar asymmetry originates. Figure 10 shows color-coded  $Y_e$  distributions in cut planes containing the dipole axis in analogy to Fig. 9 and with the same orientation, i.e., bottom is the hemisphere of largest lepton-number emission. We also show isodensity contours as white circles—the density stratification is perfectly spherical and concentric around the center of mass (which essentially coincides with the coordinate origin) because of the extreme strength of the gravity field of the PNS. The outermost contour, corresponding to  $3 \times 10^{11} \text{ g cm}^{-3}$ , is somewhat interior to the average neutrinosphere.

The four different postbounce moments correspond to the ones shown in Fig. 1 and span the time when the lepton-emission dipole begins to form (148 ms p.b.) all the way to a time when it is fully developed, but still before any noticeable decay takes place (240 ms). We see the development of a more electron-depleted region in the upper hemisphere, where a smaller lepton-number flux originates, while the bottom hemisphere, where a larger lepton-number flux originates, exhibits more electron-rich material. The growth of the hemispheric asymmetry of the lepton distribution in the PNS mantle region below the neutrinosphere is clearly visible as the compact remnant deleptonizes and contracts between  $t \sim 150$  ms (top left) and  $t = 210$  ms (bottom left). At around this later time the most extreme hemispheric difference is reached with an electron fraction difference of up to  $\Delta Y_e \sim 0.03\text{--}0.06$  on some density levels. As time and lepton emission progress, the hemispheric differences tend to decrease (bottom right).

The asymmetry of the  $Y_e$  distribution not only explains the emission dipoles of  $\nu_e$  and  $\bar{\nu}_e$ , it also explains why the number flux of heavy-lepton neutrinos,  $\nu_x$ , is somewhat amplified (on the percent level) in the direction of the smaller lepton-number flux, which is the direction of stronger  $\bar{\nu}_e$  emission



**Figure 9.** Radial evolution of the lepton-number flux in the  $11.2 M_{\odot}$  model at 210 ms p.b. (same moment as in Fig. 8). Shown is the color-coded isotropic equivalent of the lepton number flux, i.e.,  $4\pi r^2 (F_{\nu_e} - F_{\bar{\nu}_e})$  in  $10^{56} \text{ s}^{-1}$ , along angular “rays” of the transport simulation. The cut plane includes the direction of maximal lepton emission (bottom of panels) and the opposite direction of minimal lepton emission (top of cut). The average neutrinosphere is at about 35 km (white circle). The right panel is a zoom of the left one. PNS convection is clearly visible, with stronger activity in the hemisphere of maximal lepton-number flux (bottom direction).



**Figure 10.** Distribution of the electron fraction,  $Y_e$ , in the PNS and its immediate surroundings for the  $11.2 M_{\odot}$  model at the indicated p.b. times. The cut plane is the same as in Fig. 9, i.e., it contains the dipole axis with the direction of maximal lepton-number emission being downward in these panels. The color scale saturates when  $Y_e > 0.15$  and was chosen to highlight the  $Y_e$  variations in the PNS mantle region around the central, lepton-rich core and below the neutrinosphere (which roughly coincides with the outermost white circle). The white circles are isodensity contours at the levels of  $3 \times 10^{11}$ ,  $10^{12}$ ,  $3 \times 10^{12}$ ,  $10^{13}$ ,  $3 \times 10^{13}$ , and  $10^{14} \text{ g cm}^{-3}$ . Notice the development of a more strongly deleptonized shell in the upper hemisphere (direction of minimal lepton-number flux), while in the bottom hemisphere the lepton-number fraction is larger. In this hemisphere, the mass accretion rate is larger, supplying a larger amount of fresh lepton number.

(cf. Figs. 5 and 6). Because the annihilation of  $e^+e^-$  and  $\nu_e\bar{\nu}_e$  pairs yields important contributions to the  $\nu_x$  number flux, in particular at lower densities (whereas at high densities the production by nucleon-nucleon bremsstrahlung dominates; see Raffelt 2001; Buras et al. 2003; Keil, Raffelt, & Janka 2003 for details), the larger positron and  $\bar{\nu}_e$  abundances on this side of the PNS also foster the emission of heavy-lepton neutrinos.

#### 4. DRIVING MECHANISM OF LESA

##### 4.1. Asymmetry of mass-accretion flow

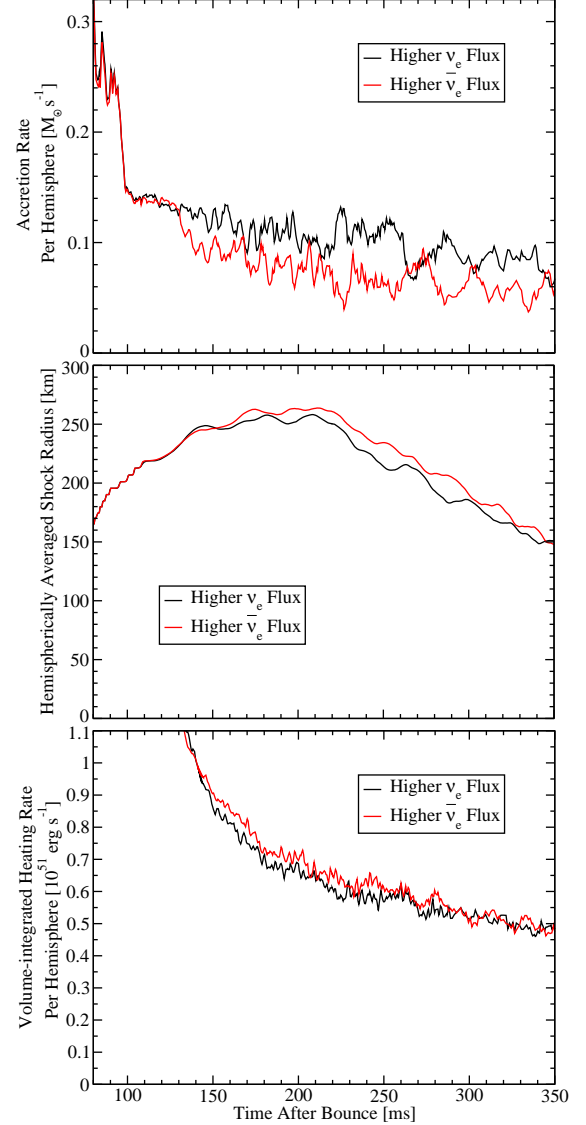
The lepton-flux asymmetry originates deep inside the PNS, below the neutrinosphere, and several phenomenological observations form a consistent picture, e.g., the lepton-emission asymmetry, the PNS convection asymmetry, the asymmetric  $Y_e$  distribution, and the small  $\nu_x$  emission asymmetry. However, these manifestations do not yet provide a hydrodynamical explanation of how these effects first arise and then stabilize themselves in a quasi-stationary pattern. Moreover, the initial growth of the dipole distribution over 100–150 ms is parallel to the growth of convective overturn in the gain region below the stalled shock wave.

The most plausible physical connection between the asymmetries deep in the PNS and hydrodynamical properties of the envelope derives from asymmetric mass-accretion flows. To study this hypothesis we consider the time evolution of the mass accretion flow in our usual two hemispheres defined by maximal and minimal lepton-number emission, shown in Fig. 11 (top). At a time when the dipole begins to form in earnest, we notice a significant hemispheric asymmetry of the mass accretion rate such that the hemisphere of larger lepton-number flux also has the larger mass accretion rate.

This flow fluctuates strongly because of convective perturbations, but on average exhibits a time-dependent anisotropy of 30–50% and on average carries considerably more fresh lepton number to the central compact object on one side than on the other. The lepton-rich flow partially deleptonizes by neutrino emission before it spreads out below the PNS surface to settle into the PNS mantle<sup>4</sup>, but it is still more lepton-rich than the deleptonized material that is already present in this region. Because it is specifically lighter (containing a higher number fraction of electrons and protons instead of heavier neutrons), the lepton-rich gas does not efficiently mix with the deleptonized plasma. Instead, it accumulates on one side of the PNS and pushes the more deleptonized fluid out of the way, towards the opposite hemisphere.

The full explanation for the  $Y_e$  distribution is actually even more complex. The accretion inflow of lepton number cannot explain the entire  $Y_e$  asymmetry in the PNS mantle. On the one hand, the accretion downflows deleptonize nearly identically during their infall from different directions, fairly independently of the local mass-flux density in the convective downdrafts that carry the accretion flow towards the PNS. Some of the greenish areas in the lower hemisphere of Fig. 10, which have no counterpart on the upper side, have possibly inherited their electrons from accretion flows. However, the red, orange and yellow bulges, which reach outward from the dense, high- $Y_e$  core most prominently in the lower hemi-

<sup>4</sup> Consistent with our discussion of the radial evolution of the lepton-emission dipole in Sec. 3.4 that was based on Fig. 8, we now independently confirm that the lepton-number loss ( $\Delta Y_e \approx 0.4$ ) associated with the accretion-rate difference between the two hemispheres,  $\Delta \dot{M} \lesssim 0.08 M_\odot \text{ s}^{-1}$  (Fig. 11), accounts for a lepton-number flux of at most  $4 \times 10^{55} \text{ s}^{-1}$  and therefore can explain at most 25% of the lepton-emission dipole.

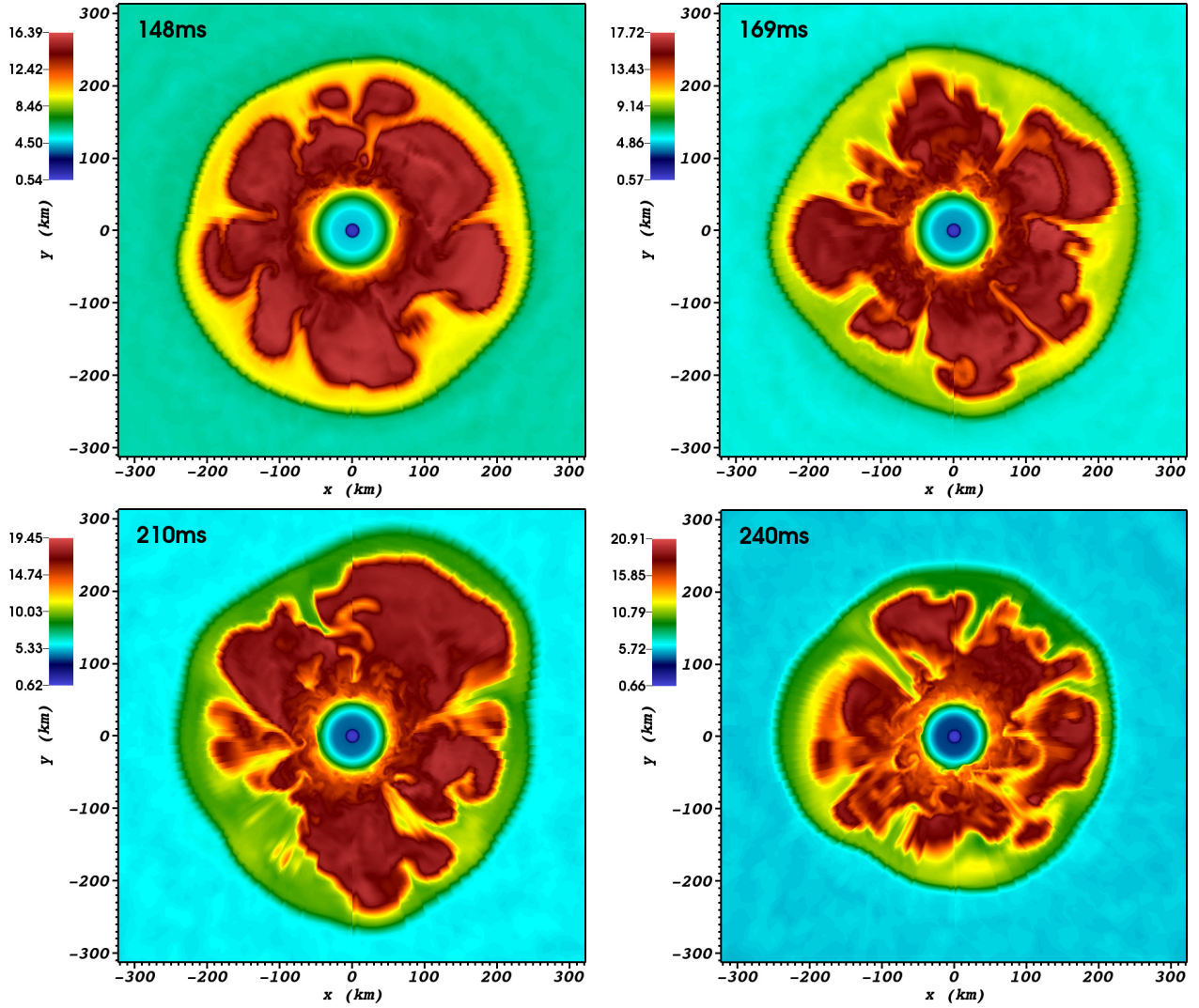


**Figure 11.** Time evolution of quantities in the postshock accretion layer of the  $11.2 M_\odot$  progenitor for the hemisphere of large lepton-number flux, i.e., large  $\nu_e$  flux (black line), and the opposite hemisphere of larger  $\bar{\nu}_e$  flux (red line). *Top:* Mass accretion rate, measured downstream of the stalled SN shock at  $r = 100 \text{ km}$ . *Middle:* Average shock radius. *Bottom:* Volume-integrated neutrino-heating rate in the gain layer (excluding the supersonic accretion downflows). The plots visualize important components of the crucial feedback loop consisting of asymmetric accretion rate, asymmetric lepton-number flux, asymmetric neutrino heating rate, and dipole deformation of the shock front as explained in the main text and Fig. 14.

sphere, cannot come from the same origin. They are located in the convective shell of the PNS, which is interior to the neutrinospheres, and they thus suggest an enhanced efficiency of the convective lepton-number transport out from the inner core. The convective region inside of the PNS can be recognized as a circular ring of short-wavelength color variations between  $\sim 12 \text{ km}$  and  $\sim 25 \text{ km}$  in the right panel of Fig. 9. This region is more pronounced in the lower hemisphere, indicating stronger PNS convection effects in this direction, by which lepton number is pulled up from the central, lepton-rich high-density core. This dredge-up explains the presence of high- $Y_e$  patches (red, orange, and yellow in Fig. 10) extending outward from the inner core region.

Convective activity inside the PNS is constrained to a shell





**Figure 12.** Entropy distribution in the postshock region of the  $11.2 M_{\odot}$  simulation at the indicated p.b. times. The cut plane is the same as in Figs. 9 and 10, i.e., it contains the dipole direction, where downward is the direction of maximum lepton-number flux. While a global asymmetry between the upper and lower hemispheres is hardly visible during the early stages when the lepton emission anisotropy just begins to develop (see Fig. 5), stronger convection in the upper hemisphere during the later stages (*bottom panels*) can be inferred from the larger buoyant bubbles and larger average shock radius on this side.

that surrounds the convectively stable core. The size of the convection cells is roughly defined by the radial scale of the active layer. Therefore, a volume-filling convective dipole mode is absent and the formation of a low-mode dipolar asymmetry of the lepton transport is puzzling. This argument supports a driving mechanism connected to the global accretion asymmetry. It seems that convective transport of lepton (electron) number in the deeper PNS mantle region might be amplified when accretion downflows impinge into the PNS, presumably because shear flows, turbulence, and gravity waves, which are instigated in the outer layers of the PNS mantle as a consequence of such violent impacts, can act in a destabilizing way on convectively nearly neutral or marginally stable stratifications. Also the contraction of the PNS might play an important role during the growth phase of the dipole mode. Postshock overturn develops in parallel to a phase of strong PNS contraction. Since the NS mantle layer settles to increasing densities, convection cannot reach a steady state in which perturbations connected to the impact of accretion downflows may be washed out on the typical timescales of small-scale lepton transport. Instead, hemi-

spheric asymmetries imprinted at early times, when matter still resides at low densities with short restoring timescales, may be carried to higher densities and thus may get frozen in for much longer periods, becoming the initial seeds for a subsequent growth towards the global dipolar asymmetry. A more detailed analysis of the dynamical interaction of accretion stream impacts in the outer layers of the PNS and convection in the contracting PNS mantle is deferred to future work.

The low-mode dipolar asymmetry of the lepton-number distribution in the PNS is therefore a consequence of the strong gravity, which on the one hand tends to spread out flows and to smoothen structures along equipotential surfaces and on the other hand defines an environment where buoyancy effects play an extremely important role.

#### 4.2. Asymmetry of gain-layer convection and shock-wave radius

One may wonder if the asymmetric accretion flow has a visible correspondence in the structure of the large-scale convection in the gain region. To investigate this question we show in Fig. 12 entropy distributions in the same cut planes



that were used in Fig. 10 for the  $Y_e$  distribution, i.e., the plane contains the dipole direction and downward is the direction of maximum lepton-number flux. In contrast to the clear hemispheric differences of the mass accretion rate in the postshock layer (Fig. 11, top panel), associated differences in the region of convective overturn are not clearly visible in the entropy cuts or in the earlier visualizations of Fig. 2. A closer inspection of the entropy cuts (Fig. 12) reveals that in the lower two panels ( $t = 210$  and  $240$  ms p.b.) the convective plumes are bigger and push the shock to a slightly larger radius in the upper hemisphere. Moreover, the convective downdrafts that carry the accretion flow to the PNS are more numerous (lower left panel) and the flow close to the PNS is more vigorous (lower right panel) on the opposite side. Because the convective mass motions are highly turbulent and time variable, however, one should be cautious with conclusions based on selected snapshots.

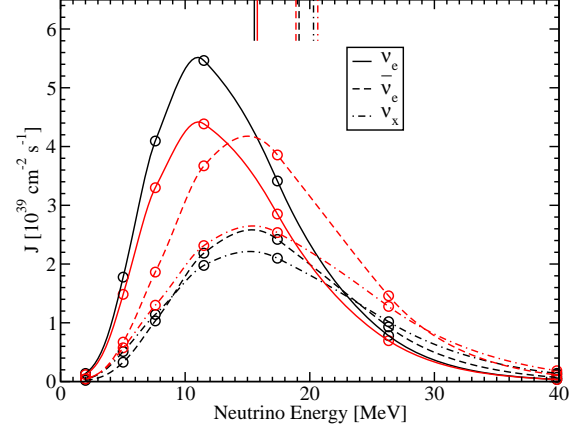
To be more quantitative, the average shock radii in both hemispheres are shown in the middle panel of Fig. 11. Indeed, from  $\sim 150$  ms onwards a clear and persistent difference, aside from fluctuations, of 10–20 km (6–7% of the average shock radius) is found.

The increased average shock-wave radius is actually the physical cause for the accretion-flow asymmetry because the spherical infall from larger radial distances is deflected and channelled preferentially toward the hemisphere of smaller shock-wave radius. One should notice the anti-correlation between mass-accretion flow and shock-wave radius in Fig. 11—the hemisphere of increased accretion flow (black line) is the hemisphere of reduced shock-wave radius. It is important in this context to remember that the preshock accretion flow is spherically symmetric except for imposed, small-scale random perturbations.

#### 4.3. Asymmetry of neutrino-heating rates

But how can this dipolar shock deformation be maintained in a quasistationary manner despite vigorous convection behind the shock? Here an interesting, self-sustaining feedback mechanism comes into play, in which the lepton-emission dipole asymmetry itself facilitates, supports, and stabilizes the conditions for its existence. The key point is that the lepton-flux asymmetry implies a neutrino-heating rate asymmetry in the gain region below the shock. In particular, the heating rate is larger in the hemisphere of smaller lepton-number flux (red lines in Fig. 11), which is the hemisphere of more vigorous gain-region convection and increased shock-wave radius. In the bottom panel of Fig. 11 we show volume-integrated heating rates in the gain layers of both hemispheres as functions of time, and indeed there is a systematic offset between the two hemispheres. Stronger neutrino heating leads to more powerful convective buoyancy and this naturally pushes the radius of the stalled shock farther out in one hemisphere compared to the opposite hemisphere, where the neutrino-energy deposition is weaker. So in the hemisphere of small lepton-number flux we have an increased heating rate, increased shock-wave radius, reduced mass-accretion flow, and therefore reduced lepton-number flux.

In order to further discuss the heating asymmetry we now consider the characteristic spectral properties of the radiated neutrinos. The  $\bar{\nu}_e$  are emitted by the PNS with significantly higher average energies than  $\nu_e$ . Typically,  $\langle \epsilon_{\bar{\nu}_e} \rangle$  exceeds  $\langle \epsilon_{\nu_e} \rangle$  by 3–3.5 MeV, averaged over all emission directions as illustrated by Fig. 4. These spectral differences also exist separately in both hemispheres, and they manifest themselves also



**Figure 13.** Energy spectra of  $\nu_e$ ,  $\bar{\nu}_e$ , and  $\nu_x$  for the  $11.2 M_\odot$  model at 210 ms p.b. (same time as in Fig. 8). The spectra are for rays in the direction of maximal (black) and minimal (red) lepton-number flux, evaluated at a distance of 400 km in the comoving frame of the accretion flow, which is spherically symmetric at this radius. We provide the monochromatic energy moment  $J = \Delta E c / (4\pi \Delta \epsilon_\nu)$  with  $\Delta E$  being the energy density in neutrino energy bin  $\Delta \epsilon_\nu$ . The tick marks at the upper edge of the plot mark the rms energies. The neutrino spectral shape is very similar in these opposite directions for each species, whereas the differences in overall normalization reflect the dipolar flux asymmetries.

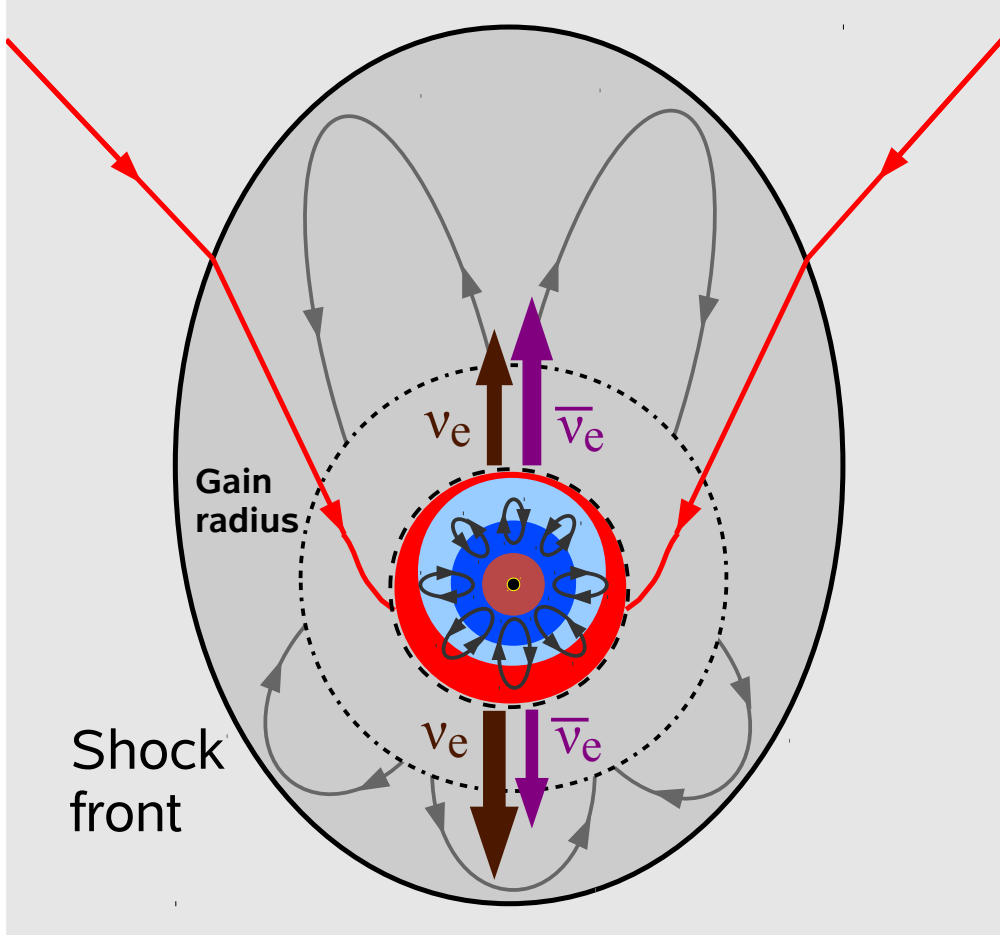
in the rms energies as shown in Fig. 13, where we display the emitted energy spectra for our previous 210 ms snapshot of the  $11.2 M_\odot$  model. Comparing the radiated energy spectra of  $\nu_e$ ,  $\bar{\nu}_e$ , and  $\nu_x$  on two selected radial rays close to the directions of maximal (black) and minimal lepton-number flux (red), the spectra differ primarily in the normalizations, whereas the spectral shapes are very similar (Fig. 13). Correspondingly, the rms energies, indicated by tick marks at the upper edge of the plot, are 15.6, 19.1 and 20.3 MeV for  $\nu_e$ ,  $\bar{\nu}_e$  and  $\nu_x$ , respectively, in the direction of maximum lepton-number flux, and very similar values of 15.8, 18.9 and 20.6 MeV are found in the opposite direction. The normalized moments of the energy spectra for each neutrino type are nearly identical in both hemispheres.

The increased heating rate in the hemisphere of small lepton-number flux (more similar  $\nu_e$  and  $\bar{\nu}_e$  number fluxes) can now be understood as follows. For the dominant processes of  $\nu_e$  absorption on free neutrons and  $\bar{\nu}_e$  absorption on free protons the heating rate per nucleon can be approximated by (cf. Janka 2001)

$$\dot{q} \propto \frac{\sigma_0}{r^2} \left( L_{\nu_e} \langle \epsilon_{\nu_e}^2 \rangle Y_n + L_{\bar{\nu}_e} \langle \epsilon_{\bar{\nu}_e}^2 \rangle Y_p \right), \quad (4)$$

where  $\sigma_0$  is the normalizing cross section,  $r^{-2}$  describes the radial flux dilution far away from the neutrinosphere,  $Y_n$  and  $Y_p$  are the number fractions of free neutrons and protons, respectively,  $L_\nu$  stands for the neutrino luminosities, and  $\langle \epsilon_\nu^2 \rangle$  denotes the squared rms energy of the energy flux. Since  $\bar{\nu}_e$  are radiated with higher rms energies, the neutrino heating will be stronger in the hemisphere where the  $\bar{\nu}_e$  number emission is relatively enhanced, despite the nearly isotropic luminosity sum of  $\nu_e$  plus  $\bar{\nu}_e$ . The effect is amplified by the fact that in this hemisphere, the  $\bar{\nu}_e$  energy flux even exceeds that of  $\nu_e$  (cf. Fig. 6, lower left panel).

Quantitatively, the numerical difference between the heating rates in the two hemispheres seen in Fig. 11 (bottom panel) is roughly 5%. This finding can easily be verified by estimating the ratio of the heating rates between the directions of low and high lepton-number flux,  $\dot{q}_{\text{low}}/\dot{q}_{\text{high}}$ . Using Eq. (4),



**Figure 14.** Schematic visualization of the physics components that provide the feedback loop for the self-sustained lepton-emission asymmetry. The outer thick, solid black line indicates the accretion shock, whose dipolar deformation is strongly exaggerated. The dotted circular line marks the gain radius and the inner dashed circular line the neutrinospheres close to the surface of the PNS. Inside the PNS, the bright-red and inner dark-red circular regions indicate the spherical density distribution around the mass center (small, black dot), whereas the displaced, blue circular shapes indicate schematically the deformation of the  $Y_e$  distribution (see Fig. 10). The black elliptical loops interior to the neutrinospheres visualize convection inside the PNS, whereas the light grey loops visualize convective overturn between gain radius and shock. PNS convection is stronger in the lower hemisphere (cf. Fig. 8), whereas gain-region convection is more powerful on the opposite side. The red lines mark accretion-stream lines, which are deflected by the deformed shock front. The brown and magenta arrows show the hemispheric asymmetry of the  $\nu_e$  and  $\bar{\nu}_e$  energy fluxes. Note that the sum of the fluxes is nearly isotropic, showing only a percent-level dipole variation, whereas the hemispheric differences of the  $\nu_e$  and  $\bar{\nu}_e$  number and energy fluxes can reach 20–30% of their average values (cf. Figs. 5 and 6). While the convective overturn in the neutrino-heating layer fluctuates strongly in time, the asymmetry of the lepton-number distribution in the PNS mantle layer and the corresponding anisotropic lepton-number emission as well as the deformation of the accretion shock can be stable for hundreds of milliseconds.

assuming  $Y_p$  and  $Y_n$  to vary little with direction, and adopting a ratio of the squared rms energies of  $\langle \epsilon_{\nu_e}^2 \rangle / \langle \epsilon_{\bar{\nu}_e}^2 \rangle \approx 1.46$  in both hemispheres (Fig. 13) as well as amplitudes of 10–15% for the dipolar asymmetry of the  $\nu_e$  and  $\bar{\nu}_e$  energy fluxes (Figs. 5 and 6), we obtain  $\dot{q}_{\text{low}}/\dot{q}_{\text{high}} \sim 1.04\text{--}1.06$ . The numerical results in the bottom panel of Fig. 11 are based on an integration over the volumes of the gain layer in both hemispheres, taking into account only the volumes of rising plumes but excluding the regions of supersonic accretion downflows, because material in the convective downdrafts ends up in the cooling layer. Energy deposited by neutrino heating in the downflows is reemitted by neutrino radiation in the cooling layer and therefore has no direct effect on the shock behavior.

## 5. OVERALL PICTURE OF THE LESA PHENOMENON

### 5.1. Two interlocking cycles

From our discussion so far a picture of the LESA phenomenon emerges that involves a machinery consisting of two major interacting parts. One consists of asymmetric PNS

convection and concomitant asymmetric lepton-number emission. The other consists of asymmetric mass-accretion regulated by asymmetric neutrino emission through asymmetric neutrino heating in the gain layer.

We re-capitulate and summarize the cog-wheels of this machinery in the sketch of Fig. 14. It is oriented in the same way as our previous cut-planes, i.e., the lepton-number emission maximum is in the downward direction. In our line plots, black curves correspond to properties in the downward direction or lower hemisphere, red curves to the upward direction (or hemisphere), which is the hemisphere of minimal lepton-number flux emission.

In the inner parts of Fig. 14, the mass center is marked by a black dot, surrounded by concentric red circular regions which show the density stratification inside the newly formed NS. The long-dashed line indicates the location of the neutrinosphere(s). Blue circles represent levels of constant electron fraction ( $Y_e$ ). The upward displacement of the light-blue region visualizes schematically a dipolar asymmetry of the deleptonization in the NS mantle region enclosed by the neu-

trinosphere: While in the top hemisphere the layer below the neutrinosphere has deleptonized more strongly due to the preceding and ongoing emission of electron neutrinos (the light-blue region there is bigger), the bottom hemisphere contains a larger fraction of electrons (indicated by the larger red area).

This dipolar asymmetry of the  $Y_e$  distribution in the PNS mantle is a consequence of a pronounced hemispheric difference in the mass flow towards the compact object. The latter accretes matter at a significantly higher rate on one side and thus receives a greater inflow of fresh lepton number in this hemisphere (bottom in Fig. 14). Even more important, however, is an indirect effect connected with the mass accretion. As the accretion streams impinge onto the PNS they instigate turbulence and gravity waves, which enhance convection in the deeper mantle layers of the PNS, dredging up electrons from the central, lepton-rich dense core (visualized in Fig. 14 by the larger convective loops in the lower hemisphere). Lepton number carried away by the outgoing neutrino fluxes is therefore replenished by electrons delivered by accretion downdrafts as well as those pulled outward in convective flows that reach deeper into the PNS core. Since the underlying processes are nonisotropic and more efficient in one hemisphere, the deleptonized mantle layer of the PNS exhibits a long-lasting dipolar asymmetry of the  $Y_e$  distribution.

The anisotropic accretion flow towards the PNS is indicated by the two red accretion-stream lines. Such an accretion asymmetry in the convectively stirred postshock layer should be understood in a time-averaged sense, emerging effectively from a strongly fluctuating accretion-flow pattern. The convective activity in the region between gain radius (short-dashed line) and shock is symbolized by the up- and down-going loops for the convective overturn motions of rising and sinking gas. The accretion asymmetry is caused by a dipolar shock deformation, which—again in a time-averaged sense—is associated with a larger radius of the accretion shock (thick, black outer ellipsoidal line) in the upper hemisphere. This leads to a deflection of the radial accretion flow when the collapsing matter crosses the shock front, because the tangential velocity component is conserved whereas the perpendicular velocity component is reduced by the flow deceleration according to the shock-jump conditions. The deflection of the postshock flow feeds, on average, the lower PNS hemisphere with a higher mass accretion rate.

In this picture, the dipole asymmetry of the neutrino lepton-number flux is a self-sustained, self-stabilizing phenomenon, because the different spectral properties of  $\nu_e$  and  $\bar{\nu}_e$  ensure more efficient neutrino heating on the side of the lower mass accretion rate and thus lower radiated lepton-number flux. Stronger heating in this hemisphere supports stronger convection and a greater shock radius, thus maintaining the shock deformation that is responsible for the deflection of the accretion flow and the enhanced mass accretion rate reaching the opposite side of the PNS. Neutrinos therefore play a crucial role in this nonradial instability, which leads to a long-lasting, stable asphericity of the postbounce accretion situation.

### 5.2. Memory effect in the PNS

The LESA effect is not “switched off” by the appearance of strong SASI activity, a surprising finding because one would imagine that violent sloshing and spiral modes would interrupt the feedback loop which is the driving cause for LESA. However, LESA has substantial inertia built into its machinery, where the  $Y_e$  distribution and related PNS convection asymmetry play the role of a flywheel that keeps going even

if the driving engine has been temporarily disabled. Once SASI has subsided, the continuing asymmetric lepton emission from the PNS region quickly restarts the engine and puts the feedback loop back into operation. This picture is not necessarily contradicted by the observation that the onset of SASI can considerably shift the LESA dipole direction as seen, for example, at 170 ms p.b. in the  $27 M_\odot$  model (bottom right panel in Fig. 3.).

How long can the PNS memory effect last? The life time of the  $Y_e$  asymmetry in the PNS depends on two competing effects, on the one hand the inflow of fresh electron number in the asymmetric accretion flow and caused by convective transport out of the high-density PNS core, and on the other hand the loss of lepton number by the anisotropic lepton fluxes, which strive for destroying the hemispheric  $Y_e$  asymmetry. The temporal decay of this asymmetry in the PNS mantle can therefore be approximately described by the following differential equation:

$$\frac{1}{2 m_u} \frac{d(\Delta Y_e M_{\text{shell}})}{dt} = \frac{1}{m_u} \left[ \Delta \dot{M} \Delta Y_e + \left( \frac{\delta(M Y_e)}{\delta t} \right)_{\text{mix}} \right] - \Delta N, \quad (5)$$

where  $\Delta Y_e$  is the difference of the electron fraction in the two hemispheres within a shell of mass  $M_{\text{shell}}$ ,  $\Delta \dot{M}$  is the mass-accretion rate difference (which we assume to carry an excess lepton fraction of  $\Delta Y_e$  into the PNS mantle,  $[\delta(M Y_e)/\delta t]_{\text{mix}}$  is the rate of electron-number change associated with enhanced convective mixing,  $\Delta N$  the neutrino-lepton flux difference between both hemispheres, and  $m_u$  the baryon mass. Equation (5) yields a rough estimate of the decay timescale:

$$t_{\text{decay}} \sim \frac{0.5 \Delta Y_e M_{\text{shell}}}{m_u \Delta N}. \quad (6)$$

In this expression we have ignored the positive contributions on the rhs of Eq. (5) because the first term turns out to be subdominant when numbers from the simulation ( $\Delta Y_e \sim 0.05$ ,  $\Delta \dot{M} \sim 0.05 M_\odot \text{ s}^{-1}$ , cf. Figs. 10 and 11) are used, and the second term is difficult to calculate without digging into the details of the dynamic interaction between the PNS convection and the impact of accretion flows on the PNS. In any case, the inflow of fresh lepton number associated with the positive source term can only stretch the decay timescale so that our estimate provides a firm lower limit. With numbers deduced from our model analysis discussed in this section,  $M_{\text{shell}} \sim 0.4 M_\odot$ ,  $\Delta Y_e \sim 0.05$  (Fig. 10), and  $\Delta N \sim 12 \times 10^{55} \text{ s}^{-1}$  (Fig. 13), we obtain  $t_{\text{decay}} \sim 100 \text{ ms}$ . Therefore, once the lepton-emission dipole has developed to its full strength, it will continue to exist for at least 100 ms even if the asymmetries of accretion and PNS convection disappear.

## 6. SUMMARY AND OUTLOOK

In this paper we have described a new type of nonradial deformation mode that we discovered in our 3D stellar core-collapse simulations using energy-dependent, three-flavor neutrino transport, applied to progenitor stars of 11.2, 20, and  $27 M_\odot$ . During the first 100–150 ms of postbounce evolution, a stationary, dipolar neutrino-emission asymmetry establishes itself. It persists throughout the postbounce accretion phase of the stalled SN shock for hundreds of ms, even in those models that show violent SASI activity for part of their postbounce evolution. This multi-dimensional phenomenon has not been identified unambiguously in any previous 2D simulation. We call the new phenomenon LESA

for “Lepton-number Emission Self-sustained Asymmetry.” LESA emerges from an instability, i.e., the spherically symmetric state is not stable and the asymmetry grows from any perturbation, no matter how small. In contrast to convection or SASI, the nature of LESA is not simply hydrodynamical, but rather a neutrino-hydrodynamical instability and as such the first of its kind identified in the SN context.

The dipole mode manifests itself most conspicuously in the lepton-number flux ( $\nu_e$  minus  $\bar{\nu}_e$ ), whose dipole amplitude can reach 100% of its  $4\pi$  directional average, i.e., in one direction the lepton-number flux can exceed twice the average, in the opposite direction it can be even somewhat negative ( $\bar{\nu}_e$  number flux exceeds that of  $\nu_e$ ). While dipole amplitudes of the individual  $\nu_e$  and  $\bar{\nu}_e$  number and energy fluxes of 10–20% can be observed in our 3D calculations of the  $11.2 M_\odot$  progenitor (and somewhat smaller ones in the  $27 M_\odot$  model), heavy-lepton neutrinos as well as the sum of  $\nu_e$  and  $\bar{\nu}_e$  exhibit only percent-level dipolar luminosity asymmetries.

The neutrino-emission dipole originates from a hemispheric asymmetry of the electron distribution in the mantle layer of the PNS interior to the neutrinospheres, although the density stratification is perfectly spherical and concentric in these regions of extreme gravitational field strength. In the hemisphere of higher  $\nu_e$  flux, convection in the deeper layers of the PNS mantle is enhanced compared to the opposite side and dredges up electrons more efficiently from the dense, lepton-rich central core. These electrons are mixed outward towards the neutrinospheres and lead to less depleted conditions in one hemisphere, supporting the higher  $\nu_e$  flux. The convective activity seems to be instigated and fostered by shear flows, turbulent motions, and gravity waves caused by the violent impacts of accretion streams in the neutrinospheric region. This connection is suggested by the observed correlation between PNS-convection asymmetry and a considerable asymmetry of the mass-accretion flow which is stronger in the hemisphere of enhanced PNS convection. The accretion asymmetry also contributes to the lepton-number emission dipole, because the accretion streams carry electron-rich matter and thus supply the PNS with fresh lepton number, but this effect is subdominant.

The global accretion asymmetry is maintained by anisotropic neutrino heating in the gain layer behind the stalled SN shock, because  $\bar{\nu}_e$  leave the neutrinosphere with higher mean energy than  $\nu_e$ . Therefore, neutrino heating is stronger on the side of lower lepton-number flux, despite the nearly isotropic energy flux of  $\nu_e$  plus  $\bar{\nu}_e$ . Stronger neutrino heating enhances convective overturn in the postshock layer, pushes the shock to a larger stagnation radius and thus produces a dipolar deformation of the shock surface. This shock deformation in turn deflects the accretion flow falling through the shock and, in the time-averaged sense, amplifies the accretion flux to the hemisphere of the PNS facing away from the greater shock radius (Fig. 14).

Anisotropic neutrino heating therefore establishes a feedback mechanism between the neutrino-emission asymmetry on one side and shock deformation and accretion asymmetry on the other. It thus mediates a complex, mutual dependence between lepton-number transport by neutrino fluxes and convection inside the PNS on the one hand and anisotropic convective overturn in the gain layer on the other. This feedback, which involves neutrinos as crucial players, allows the global dipolar asymmetry to become a self-sustained phenomenon, which exists in quasi-stationary conditions over many dynamical timescales despite the presence of vigorous and highly

time-dependent convective overturn in the postshock region and even through phases of violent SASI activity. Stochastic fluctuations of this convective overturn or of the convection in the PNS mantle are probably responsible for initiating the development of the hemispheric asymmetry. The convective SN core seems to be generically unstable against such a dipolar mode of asymmetry.

LESA could have important implications for a variety of physical processes in the SN core, most importantly nucleosynthesis in the neutrino-heated ejecta, and potentially NS kicks and neutrino-flavor conversion.

Concerning nucleosynthesis, we recall that charged-current reactions of  $\nu_e$  and  $\bar{\nu}_e$  with neutrons and protons do not only heat the SN blast wave but also set the n/p ratio in the neutrino-driven outflow and thus determine the nucleosynthesis conditions in the innermost SN ejecta. Since  $\nu_e$  absorption converts neutrons to protons while  $\bar{\nu}_e$  captured on protons create neutrons, the exposure to a higher flux of  $\bar{\nu}_e$  tends to neutronize the expelled matter. The lepton-number emission asymmetry could persist until the explosion sets in or even beyond, fuelled by continued anisotropic PNS convection and/or asymmetric accretion beyond the onset of the explosion. In this case a considerable hemispheric asymmetry of the electron fraction in the ejecta could be expected with possibly favorable conditions for neutron-rich material in the direction where the  $\bar{\nu}_e$  flux has its emission maximum. We speculate that the O-Ne-Mg core explosion of Wanajo, Janka, & Müller (2011), where convective overturn but not SASI played a role, may be the only case where we have encountered the dipolar lepton-emission asymmetry in a 2D model. The moderate hemispheric differences of  $Y_e$  in the early neutrino-driven wind (with variations in the range  $0.46 \leq Y_e \leq 0.54$ ) in this simulation might give an impression of the corresponding effects that could be obtained in future 3D explosions.

Asymmetric neutrino emission imparts a recoil on the nascent NS. We assume a dipolar emission anisotropy of the total neutrino-energy loss rate (the summed contributions of  $\nu$  and  $\bar{\nu}$  of all flavors),

$$\frac{d\dot{E}_{\text{tot}}}{d\Omega} = \frac{\dot{E}_{\text{tot}}}{4\pi} (1 + \alpha \cos \vartheta), \quad (7)$$

where  $\alpha$  is the dipole amplitude and  $\vartheta$  the zenith angle relative to the dipole direction. In this case the NS acceleration is

$$a_{\text{NS}} = \frac{1}{M_{\text{NSC}}} \int_{4\pi} d\Omega \frac{d\dot{E}_{\text{tot}}}{d\Omega} \cos \vartheta = \frac{\alpha}{3c} \frac{\dot{E}_{\text{tot}}}{M_{\text{NS}}}. \quad (8)$$

With  $\dot{E}_{53} \equiv \dot{E}_{\text{tot}}/(10^{53} \text{ erg s}^{-1})$  and  $M_{1.5} \equiv M_{\text{NS}}/(1.5 M_\odot)$  we obtain

$$a_{\text{NS}} \approx 37 \frac{\alpha}{0.01} \frac{\dot{E}_{53}}{M_{1.5}} \text{ km s}^{-2}. \quad (9)$$

If  $\alpha \sim 0.01$ – $0.02$  and the duration of the emission asymmetry lasts only some hundred milliseconds, corresponding to the duration of the accretion phase, the recoil velocity will not exceed several  $10 \text{ km s}^{-1}$ , depending on the time-integrated neutrino-energy release  $E_{\text{tot}}$ . But the NS kick velocity could reach  $100$ – $200 \text{ km s}^{-1}$  for a canonical value of  $3 \times 10^{53} \text{ erg}$  for the NS gravitational binding energy, if the neutrino-emission dipole continues to exist for the whole period of PNS neutrino cooling. With the luminosity maximum coinciding with the  $\bar{\nu}_e$  emission peak in our 3D simulations, the NS acceleration will point in the direction of the strongest  $\nu_e$  emission. Even in the optimistic (and highly speculative) case that the



neutrino-emission dipole survives for seconds, however, the estimated recoil velocity is dwarfed by those that can typically be expected from the “gravitational tug-boat mechanism” associated with the anisotropic ejection of matter in 3D simulations of SN explosions (Wongwathanarat, Janka, & Müller 2010, 2013). We conclude that LESA is unlikely to be a major source for NS kicks.

Another small but amusing mechanical consequence of LESA is an angular momentum transfer, i.e., a spin-up of the nascent NS. Weak interactions violate parity maximally, implying that a relativistic  $\nu_e$  has negative helicity and carries the spin angular momentum  $-\hbar/2$  relative to its direction of motion, whereas a  $\bar{\nu}_e$  has positive helicity and carries  $+\hbar/2$ . We denote the lepton-number flux dipole amplitude with  $A_{\text{Dipole}}$ , i.e., the quantity plotted in Fig. 3. The angular momentum transfer rate then has the magnitude

$$\dot{J} = \frac{\hbar}{2} \frac{A_{\text{Dipole}}}{3}, \quad (10)$$

because our normalization of the dipole amplitude implies that it is three times the total lepton-number flux projected on the dipole direction. With a typical value  $A_{\text{Dipole}} = 3 \times 10^{56} \text{ s}^{-1}$  and recalling that  $\hbar = 1.054 \times 10^{-27} \text{ cm}^2 \text{ g s}^{-1}$  we find a typical angular-momentum transfer rate of  $\dot{J} = 5 \times 10^{28} \text{ cm}^2 \text{ g s}^{-2}$ . We recall that the moment of inertia of a homogeneous sphere with mass  $M$  and radius  $R$  is  $I = 2MR^2/5$  and its angular momentum is  $J = I2\pi f$  with  $f$  the rotation frequency. Using as benchmark values  $M = 1.5 M_\odot$  and  $R = 15 \text{ km}$ , a typical PNS spin-up rate is of the order of  $\dot{f} \sim 3 \times 10^{-18} \text{ Hz s}^{-1}$ , a very small value indeed. A much larger effect, however, is non-radial neutrino emission that can transfer orbital angular momentum and cause a spin-down of a rotating NS as first shown by Mikaelian (1977) and Epstein (1978).

Our entire study has ignored neutrino flavor conversion. The LESA phenomenon depends on a subtle hemispheric asymmetry of neutrino heating rates. Certainly this effect would be modified if the  $\nu_e$  and  $\bar{\nu}_e$  fluxes would partially swap flavor with  $\nu_x$  and  $\bar{\nu}_x$  which have different spectral properties and different number fluxes. Moreover, flavor conversion also modifies the neutrino influence on the n/p ratio in the context of nucleosynthesis as first pointed out by Qian et al. (1993) and Qian & Fuller (1995).

The thorniest problem in the context of neutrino flavor conversion is the role of neutrino-neutrino refraction which causes many complications because of the feedback of flavor conversion on itself (Duan, Fuller & Qian 2010). The justification for ignoring flavor conversion in the dense region below the stalled shock wave is the so-called multi-angle matter effect, which tends to suppress self-induced flavor conversion (Esteban-Pretel et al. 2008; Sarikas et al. 2012; Raffelt, Sarikas & de Sousa Seixas 2013; Chakraborty et al. 2011; Saviano et al. 2012; Chakraborty et al. 2014). In particular, Dasgupta, O’Connor & Ott (2012) have studied the onset of self-induced flavor conversion in a somewhat simplified 3D model. These authors conclude that flavor conversion always begins outside the shock wave.

It is conceivable, however, that these conclusions must be modified in the LESA context, notably in those directions where the lepton number flux is small. The asymmetry between the  $\nu_e$  and  $\bar{\nu}_e$  number fluxes, sometimes denoted with the parameter  $\epsilon$ , is a crucial ingredient for the stability of the neutrino flux in flavor space (Esteban-Pretel et al. 2007). Moreover, the LESA phenomenon also modifies the electron-

density profile which defines the matter effect for neutrino flavor oscillations. Therefore, it remains to be verified that flavor conversion is indeed irrelevant for the LESA phenomenon.

The observations reported in this paper raise many interesting questions. It is obvious that the LESA phenomenon needs much more work and analysis to develop a full understanding, especially concerning how asymmetric PNS convection is stimulated by asymmetric mass accretion. Many of our explanations remain tentative and require further confirmation.

In particular, further studies are necessary to reveal how generic the lepton-number emission dipole is. How exactly does its amplification work, what is the underlying mechanism? What is the role of the PNS contraction in this context, and, if it is important, how sensitive is the phenomenon to the nuclear equation of state and the neutrino opacities? How big is the saturation amplitude of LESA and what does it depend on? Could its amplitude be larger than in our present 3D simulations and could its dipolar neutrino-heating asymmetry affect the onset of neutrino-driven SN explosions? How long does LESA last? Does LESA require the inner engine of hemispherically asymmetric PNS convection as a necessary ingredient or is its role only that of an amplifier of the lepton-number flux asymmetry and that of a stabilizing factor which enables long-term memory? A feedback loop seems possible that is solely based on the outer engine, in which the asymmetric accretion and lepton-number emission on the one hand is intertwined with the dipolar neutrino-heating asymmetry and shock deformation on the other. Answers to these questions are indispensable to reach firm conclusions on the importance of LESA for NS kicks, the explosion mechanism and asymmetries, and SN nucleosynthesis.

Linear growth studies would help to develop deeper insights. It would be especially useful to construct toy models that capture the essential parts of the mechanism but reduce its complexity and thus allow a better control of the interplay of its different components. Such studies would be particularly useful because numerical models are always prone to artifacts. For example, it is unclear whether our findings are affected by approximations involved in our treatment, e.g., the ray-by-ray-plus transport, which does not include nonradial neutrino fluxes, the use of a monopole description of the gravitational potential, or the spherical core of 10 km radius, which fixes the PNS to its location at the grid center. It is therefore essential that other groups investigate their neutrino-hydrodynamics simulations for hints of effects similar to our LESA phenomenon.

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## REFERENCES

- Bethe, H. A. 1990, *Rev. Mod. Phys.*, 62, 801
- Blondin, J. M., Mezzacappa, A., & DeMarino, C. 2003, *ApJ*, 584, 971
- Blondin, J. M. & Mezzacappa, A. 2006, *ApJ*, 642, 401
- Blondin, J. M. & Mezzacappa, A. 2007, *Nature*, 445, 58
- Blondin, J. M. & Shaw, S. 2007, *ApJ*, 656, 366
- Buras, R., Janka, H.-Th., Keil, M., Raffelt, G. G., & Rampp, M. 2003 *ApJ*, 587, 320
- Buras, R., Janka, H.-T., Rampp, M., & Kifonidis, K. 2006a, *A&A*, 457, 281
- Buras, R., Rampp, M., Janka, H.-T., & Kifonidis, K. 2006b, *A&A*, 447, 1049
- Burrows, A. & Fryxell, B. A. 1992, *Science*, 258, 430
- Burrows, A., Hayes, J., & Fryxell, B. A. 1995, *ApJ*, 450, 830
- Burrows, A. & Lattimer, J. M. 1988, *Phys. Rep.*, 163, 51
- Chakraborty, S., Fischer, T., Mirizzi, A., Saviano, N., & Tomàs, R. 2011, *Phys. Rev. Lett.*, 107, 151101
- Chakraborty, S., Mirizzi, A., Saviano, N., & de Sousa Seixas, D. 2014, *arXiv:1402.1767*
- Colella, P., & Woodward, P. R. 1984, *J. Comp. Phys.*, 54, 174
- Couch, S. M. 2013, *ApJ*, 775, 35
- Couch, S. M. & O'Connor, E. P. 2013, *arXiv:1310.5728*
- Dessart, L., Burrows, A., Livne, E., & Ott, C. D. (2006), *ApJ*, 645, 534
- Dolence, J. C., Burrows, A., Murphy, J. W., & Nordhaus, J. 2013, *ApJ*, 765, 110
- Dasgupta, B., O'Connor, E. P., & Ott, C. D. 2012, *Phys. Rev. D*, 85, 065008
- Duan, H., Fuller, G. M., & Qian, Y.-Z. 2010, *Ann. Rev. Nucl. Part. Sci.*, 60, 569
- Epstein, R. 1978, *ApJ*, 219, L39
- Epstein, R. 1979, *MNRAS*, 188, 305
- Esteban-Pretel, A., Pastor, S., Tomàs, R., Raffelt, G. G., & Sigl, G. 2007 *Phys. Rev. D*, 76, 125018
- Esteban-Pretel, A., et al. 2008, *Phys. Rev. D*, 78, 085012
- Fernández, R. 2010, *ApJ*, 725, 1563
- Foglizzo, T. 2002, *A&A*, 392, 353
- Foglizzo, T., Galletti, P., Scheck, L., & Janka, H.-Th. 2008, *ApJ*, 654, 1006
- Foglizzo, T., Scheck, L., & Janka, H.-Th. 2006, *ApJ*, 652, 1436
- Foglizzo, T., Masset, F., Guilet, J., & Durand, G. 2012, *Phys. Rev. Lett.*, 108, 051103
- Fryer, C. L. & Warren, M. S., 2002, *ApJ*, 574, L65
- Fryer, C. L. & Warren, M. S., 2004, *ApJ*, 601, 391
- Fryxell, B. A., Müller, E., & Arnett, D. 1989, *Max-Planck-Institut für Astrophysik*, Preprint Nr. 449
- Guilet, J. & Fernández, R. 2013, *arXiv:1310.2616*
- Guilet, J. & Foglizzo, T. 2012, *MNRAS*, 421, 546
- Hanke, F., Marek, A., Müller, B., & Janka, H.-Th. 2012, *ApJ*, 755, 138
- Hanke, F., Müller, B., Wongwathanarat, A., Marek, A., & Janka, H.-Th. 2013, *ApJ*, 770, 66
- Herant, M., Benz, W., & Colgate, S. 1992, *ApJ*, 395, 642
- Herant, M., Benz, W., Hix, W. R., Fryer, C. L., & Colgate, S. A. 1994, *ApJ*, 435, 339
- Iwakami, W., Kotake, K., Ohnishi, N., Yamada, S., & Sawada, K. 2008, *ApJ*, 678, 1207
- Iwakami, W., Ohnishi, N., Kotake, K., Yamada, S., & Sawada, K. 2009, *Ap&SS*, 322, 43
- Janka, H.-Th. 2001, *A&A*, 368, 527
- Janka, H.-Th., Buras, R., Kifonidis, K., Plewa, T., & Rampp, M. 2003, in: *From Twilight to Highlight: The Physics of Supernovae*, Eds. W. Hillebrandt & B. Leibundgut, Springer, Berlin, p. 39
- Janka, H.-Th., Buras, R., Kifonidis, K., Rampp, M., & Plewa, T. 2004, in: *Stellar Collapse*, Ed. C. L. Fryer, Kluwer, Dordrecht, p. 65
- Janka, H.-Th., Hanke, F., Hudepohl, L., Marek, A., Müller, B. & Obergaulinger, M. 2012, *PTEP* 2012, 01A309
- Janka, H.-Th. & Müller, E. 1993, in: *Frontiers of Neutrino Astrophysics*, Eds. Y. Suzuki & K. Nakamura, p. 203
- Janka, H.-Th. & Müller, E. 1995, *ApJ*, 448, L109
- Janka, H.-Th. & Müller, E. 1996, *A&A*, 306, L167
- Keil, W., Janka, H.-Th., & Müller, E. 1996, *ApJ*, 473, L111
- Keil, W., Raffelt, G. G., & Janka, H.-Th. 2003, *ApJ*, 590, 971
- Lattimer, J. M., & Swesty, F. D. 1991, *Nucl. Phys. A*, 535, 331
- Lund, T., Marek, A., Lunardini, C., Janka, H.-Th., Raffelt, G. 2010, *Phys. Rev. D*, 82, Issue, 063007
- Marek, A., & Janka, H. 2009, *ApJ*, 694, 664
- Marek, A., Janka, H.-Th., & Müller, E. 2009, *A&A*, 496, 475
- Marek, A., Dörmelmeier, H., Janka, H.-T., Müller, E., & Buras, R. 2006, *A&A*, 445, 273
- Mezzacappa, A., Calder, A. C., Bruenn, S. W., Blondin, J. M., Guidry, M. W., Strayer, M. R., & Umar, A. S. 1998, *ApJ*, 495, 911
- Mikaelian, K. O. 1977, *ApJ*, 214, L23
- Miller, D. S., Wilson, J. R., & Mayle, R. W. 1993, *ApJ*, 415, 278
- Müller, B., Janka, H.-T., & Marek, A. 2012a, *ApJ*, 756, 84
- Müller, B., Janka, H.-T., & Heger, A. 2012b, *ApJ*, 761, 72
- Müller, B., Janka, H.-Th., & Marek, A. 2013, *ApJ*, 766, 43
- Müller, E. & Janka, H.-Th. 1994, in: *Reviews in Modern Astronomy*, 7, Ed. G. Klare, Astronomische Gesellschaft, Hamburg, p. 103
- Müller, E. & Janka, H.-Th. 1997, *A&A*, 317, 140
- Müller, E., Janka, H.-Th., & Wongwathanarat, A. 2012, *A&A*, 537, A63
- Murphy, J. W. & Burrows, A. 2008, *ApJ*, 688, 1159
- Murphy, J. W., Ott, C. D., & Burrows, A. 2009, *ApJ*, 707, 1173
- Nordhaus, J., Burrows, A., Almgren, A., & Bell, J. 2010, *ApJ*, 720, 694
- Nordhaus, J., Brandt, T. D., Burrows, A., Livne, E., & Ott, C. D. 2010, *Phys. Rev. D*, 82, 103016
- Nordhaus, J., Brandt, T. D., Burrows, A., & Almgren, A. 2012, *MNRAS*, 423, 1805
- Qian, Y.-Z. & Fuller, G. M. 1995, *Phys. Rev. D*, 52, 656
- Qian, Y.-Z., Fuller, G. M., Mathews, G. J., Mayle, R. W., Wilson, J. R., & Woosley, S. E. 1993, *Phys. Rev. Lett.*, 71, 1965
- Raffelt, G. G. 2001, *ApJ*, 561, 890
- Raffelt, G. G., Sarikas, S., & de Sousa Seixas, D. 2013, *Phys. Rev. Lett.*, 111, 091101
- Rampp, M., & Janka, H.-T. 2002, *A&A*, 396, 361
- Rantsiou, E., Burrows, A., Nordhaus, J., & Almgren, A. 2010, *ApJ*, 732, 57
- Sarikas, S., Raffelt, G. G., Hudepohl, L., & Janka, H.-T. 2012, *Phys. Rev. Lett.*, 108, 061101
- Saviano, N., Chakraborty, S., Fischer, T., & Mirizzi, A. 2012, *Phys. Rev. D*, 85, 113002
- Scheck, L., Plewa, T., Janka, H.-Th., Kifonidis, K., & Müller, E. 2004, *Phys. Rev. Lett.*, 92, 011103
- Scheck, L., Kifonidis, K., Janka, H.-Th., & Müller, E. 2006, *A&A*, 457, 963
- Scheck, L., Janka, H.-Th., Foglizzo, T., & Kifonidis, K. 2008, *A&A*, 477, 931
- Tamborra, I., Hanke, F., Müller, B., Janka, H.-Th., & Raffelt, G. 2013, *Phys. Rev. Lett.*, 111, 121104
- Takiwaki, T., Kotake, K., & Suwa, Y. 2013, *arXiv:1308.5755*
- Wanajo, S., Janka, H.-Th., & Müller, B. 2011, *ApJ*, 726, L15
- Wongwathanarat, A., Janka, H.-Th., & Müller, E. 2010, *ApJ*, 725, L106
- Wongwathanarat, A., Janka, H.-Th., & Müller, E. 2013, *A&A*, 552, A126
- Woosley, S. E. & Heger, A. 2007, *PhR*, 442, 269
- Woosley, S. E., Heger, A., & Weaver, T. A. 2002, *Rev. Mod. Phys.*, 74, 1015
- Yamasaki, T. & Foglizzo, T. 2008, *ApJ*, 679, 607